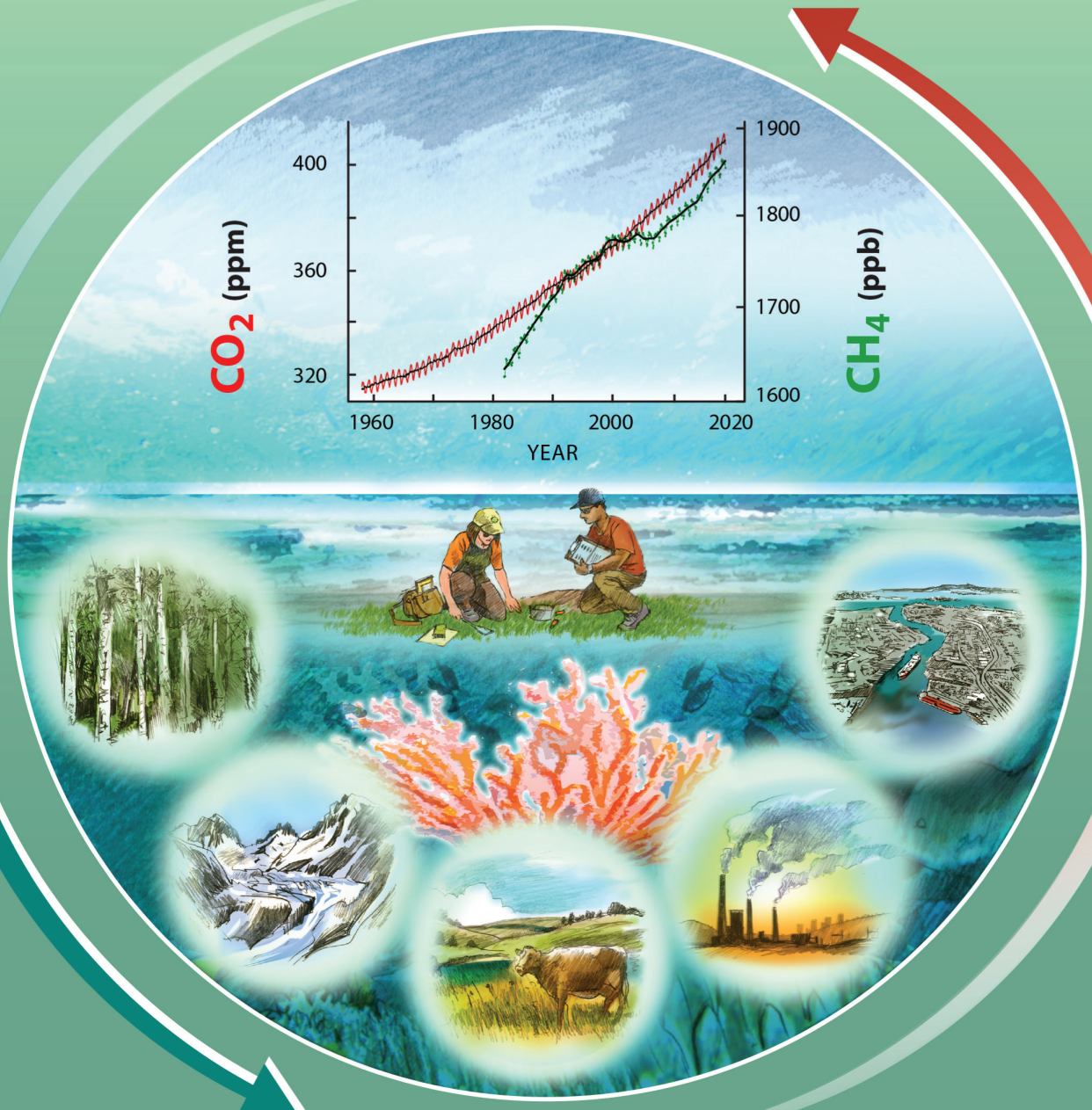
U.S. Global Change Research Program

Second State of the Carbon Cycle Report



A Sustained Assessment Report

Second State of the Carbon Cycle Report

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U.S. Global Change Research Program

Report available online at carbon2018.globalchange.gov

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Front Cover

North American carbon cycling illustration, courtesy Ron Oden, University of Nevada, Reno.

This graphic represents the dynamic nature of carbon stocks and fluxes in the United States, Canada, and Mexico described in the *Second State of the Carbon Cycle Report*.

- The center sketch of researchers taking soil samples pays tribute to the hundreds of scientists who served as authors for this report and the thousands of researchers whose data were used throughout the document.
- Arrows depict carbon emissions to the atmosphere (red) and carbon uptake by different land types and aquatic environments (teal), processes described in Ch. 1: Overview of the Global Carbon Cycle and Ch. 2: The North American Carbon Budget.
- Plotted data—collected by the National Oceanic and Atmospheric Administration's Earth System Research Laboratory—show monthly means of atmospheric carbon dioxide (CO_2) concentrations (red curve in parts per million) taken at the Mauna Loa Observatory and monthly means of methane (CH_4) concentrations (green curve in parts per billion) from globally averaged marine surface sites. Deseasonalized data are depicted by the black lines (Ch. 8: Observations of Atmospheric Carbon Dioxide and Methane).
- Coral reefs, fish, and beaches represent carbon processes in coastal waters (Ch. 15: Tidal Wetlands and Estuaries and Ch. 16: Coastal Ocean and Continental Shelves). These are key areas experiencing carbon cycle changes due to direct effects of increasing CO_2 (Ch. 17: Biogeochemical Effects of Rising Atmospheric Carbon Dioxide).
- Forests (first inset, lower left) and their soils represent the largest terrestrial carbon sink in North America. Factors influencing the strength of this sink and trends in disturbances such as wildfire, insects, and land-use change are described in Ch. 9: Forests.
- Mountains with melting glacier (second inset, lower left) illustrate the effects of greenhouse gas–induced warming on carbon cycling, particularly in high-latitude and boreal areas (Ch. 11: Arctic and Boreal Carbon).
- Pastoral scene (center inset, bottom) captures the interdependent carbon cycling processes among different terrestrial and aquatic systems (Ch. 5: Agriculture, Ch. 7: Tribal Lands, Ch. 10: Grasslands, Ch. 12: Soils, Ch. 13: Terrestrial Wetlands, and Ch. 14: Inland Waters).
- Power plant (second inset, lower right) illustrates carbon fluxes from the energy sector and other human systems and their potential impact on future carbon cycling (Ch. 3: Energy Systems and Ch. 19: Future of the North American Carbon Cycle).
- Coastal city and port (first inset, lower right) represent the many ways carbon is embedded in social systems and the different levels of information and governance involved in carbon decision making (Ch. 4: Understanding Urban Carbon Fluxes, Ch. 6: Social Science Perspectives on Carbon, and Ch. 18: Carbon Cycle Science in Support of Decision Making).

See inside back cover for image credits for chapter banners, section fronts, and back cover.

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Table of Contents

Front Matter

Highlights 1
Preface 5
Executive Summary 21

Section I: Synthesis

Chapter 1: Overview of the Global Carbon Cycle 42
Chapter 2: The North American Carbon Budget 71

Section II: Human Dimensions of the Carbon Cycle

Chapter 3: Energy Systems 110
Chapter 4: Understanding Urban Carbon Fluxes 189
Chapter 5: Agriculture 229
Chapter 6: Social Science Perspectives on Carbon 264
Chapter 7: Tribal Lands 303

Section III: State of Air, Land, and Water

Chapter 8: Observations of Atmospheric Carbon Dioxide and Methane 337
Chapter 9: Forests 365
Chapter 10: Grasslands 399
Chapter 11: Arctic and Boreal Carbon 428
Chapter 12: Soils 469
Chapter 13: Terrestrial Wetlands 507
Chapter 14: Inland Waters 568
Chapter 15: Tidal Wetlands and Estuaries 596
Chapter 16: Coastal Ocean and Continental Shelves 649

Section IV: Consequences and Ways Forward

Chapter 17: Biogeochemical Effects of Rising Atmospheric Carbon Dioxide 690
Chapter 18: Carbon Cycle Science in Support of Decision Making 728
Chapter 19: Future of the North American Carbon Cycle 760

Appendices

Appendix A: Report Development Process 810
Appendix B: Information Quality in the Assessment 818
Appendix C: Selected Carbon Cycle Research Observations and Measurement Programs 821
Appendix D: Carbon Measurement Approaches and Accounting Frameworks 834
Appendix E: Fossil Fuel Emissions Estimates for North America 839
Appendix F: Acronyms, Abbreviations, and Units 844
Appendix G: Glossary 851

Highlights

The *Second State of the Carbon Cycle Report* (SOCCR2) provides a current state-of-the-science assessment of the carbon cycle in North America (i.e., the United States, Canada, and Mexico) and its connection to climate and society (see Box 1, What Is SOCCR2?, this page). Information from the report is relevant to climate and carbon research as well as to management practices in North America and around the world. This general overview provides abbreviated highlights of some of the many significant findings from the 19 chapters in SOCCR2.

Carbon Dynamics in North America and the United States in a Global Context

Land ecosystems and the ocean play a major role in the removal and sequestration of carbon dioxide (CO_2) from the atmosphere. From 2007 to 2016, these reservoirs annually removed and stored an average of about 5.4 billion metric tons of carbon that otherwise would have remained in the atmosphere—about half the amount emitted during that period. About 11% to 13% of global ecosystem carbon removal can be attributed to North American ecosystems. Whether the land and ocean will continue to absorb similar amounts of carbon in future years is unclear, since changes in climate, human activities, and ecosystem responses may alter future long-term removals of carbon from the atmosphere. Although North America contributed substantially to global atmospheric carbon emissions over the past decade, its total carbon emissions due to fossil fuel use (referred to in this document as "fossil fuel emissions") decreased by about 23 million metric tons of carbon per year. Meanwhile, global emissions continued to increase, thus reducing the relative contribution of North America to total fossil fuel emissions from 24% in 2004 to less than 17% in 2013.

In addition to reducing the use of fossil fuels, mitigation and management activities in North

Box 1. What Is SOCCR2?

Authored by more than 200 scientists from the United States, Canada, and Mexico, the *Second State of the Carbon Cycle Report* (SOCCR2) provides an up-to-date assessment of scientific knowledge of the North American carbon cycle. This comprehensive report addresses North American carbon fluxes, sources, and sinks across atmospheric, aquatic, and terrestrial systems, as well as relevant perspectives from scientific observations and modeling, decision support, carbon management, and social sciences. The report presents Key Findings and actionable information on the observed status and trends within the North American carbon cycle, as influenced by natural and human-induced factors. These findings are based on multidisciplinary research that includes experimental, observational, and modeling studies from the last decade. Intended for a diverse audience that includes scientists, decision makers in the public and private sectors, and communities across the United States, North America, and the world, SOCCR2 provides information to inform mitigation and adaptation policies and management decisions related to the carbon cycle and climate change. It also will help support improved coordination for pertinent research, monitoring, and management activities necessary to respond to global change. SOCCR2 informs policies but does not prescribe or recommend them.

America and around the world include afforestation and reduced deforestation, restoration of coastal[1] and terrestrial wetlands, and improved land-management practices in forests, grasslands, and croplands. These activities can maintain or increase ecosystem carbon sinks (i.e., carbon storage or removal) while decreasing the sources or emissions of carbon to the atmosphere. However, Arctic warming and disturbances such as pest outbreaks, wildfires, and destruction of wetlands may disrupt and decrease carbon removal, thereby releasing previously removed carbon back to the atmosphere (see Box 2, Why Is the Carbon Cycle Important?, this page).

Fossil Fuels and Economic Impacts

Over the past decade, fossil fuel emissions continued to be by far the largest North American carbon source. The United States is currently responsible for about 80% to 85% of fossil fuel emissions from North America. The financial crisis around 2008 contributed to a reduction in North American fossil fuel emissions as economic and industrial growth slowed. Yet, as the economy has recovered, increased energy efficiency and economic structural changes have enabled economic growth while continuing the trend of lowering CO_2 emissions. Over the last decade, North America has reduced its CO_2 emissions from fossil fuels by about 1% per year, as the result of various market, technology, and policy drivers.

A Changing Landscape

At the global level, land-use change due to social, demographic, and economic trends is projected to contribute between 11 and 110 billion metric tons of carbon to the atmosphere by 2050. However, the trend in the United States is the opposite: current assessments suggest that better forest management practices, as well as reforestation and other improvements in ecosystem and resource management, are helping the nation decrease its carbon emissions.

[1] Coasts and coastal ecosystems in SOCCR2 include mangroves, tidal marshes, and seagrass meadows.

Box 2. Why Is the Carbon Cycle Important?

The carbon cycle encompasses the flow, storage, and transformation of carbon compounds that are central to life and to the production of food, fiber, and energy. Carbon also helps regulate Earth's climate, including temperature, weather events, and more. This report assesses the complex, interconnected ecological and societal aspects of the carbon cycle, illustrating the importance of the carbon cycle to ecosystems, regions, and communities and projecting possible future changes to the carbon cycle and impacts on humans and ecosystems, while also presenting relevant issues for decision makers.

Ocean Acidification

Ocean acidification, or the decrease in seawater pH due to increased oceanic CO_2 absorption, can adversely affect many marine populations and ecosystem processes, including organisms that people rely on for food and ecosystem services that sustain economies and cultures throughout North America. Acidification is occurring faster in circumpolar regions and some coastal areas than in the open ocean. For example, over the past decade, Arctic and Pacific Northwest coastal waters have experienced longer, more frequent periods of lower pH, putting livelihoods reliant on these areas at increased risk. Maintaining and expanding existing ocean observing programs, as well as continuing coordinated work with stakeholders, will be critical to ensure a healthier ocean, resilient communities, and strong economies.

Arctic Changes

The environment of high-latitude regions, such as the Arctic, is changing at a faster pace than the rest of North America. For example, Arctic surface air

temperatures are rising about 2.5 times faster than the global average. This increase can destabilize permafrost soils (i.e., soil that remains permanently frozen at some depth) and surrounding landscapes, which exist throughout the Arctic and store almost twice the amount of carbon currently contained in the atmosphere. Warming temperatures can release this stored carbon into the atmosphere. In addition, accelerated warming increases the frequency and intensity of fires, which also release large amounts of carbon stored in Arctic permafrost, surface soils, and vegetation.

Carbon in Crops

Most carbon in croplands is stored in the soil and is sensitive to increasing temperatures, land-use changes, and agricultural development and practices, all of which can result in the loss of carbon from the soil to the atmosphere. Soil carbon stocks can be increased or stabilized by incorporating practices that 1) keep the land covered with plants, especially deep-rooted perennials and cover crops, 2) protect the soil from erosion (e.g., by decreasing tillage), and 3) improve nutrient management. Additionally, optimizing nitrogen fertilizer management to sustain crop yields and reduce nitrogen losses to air and water can help reduce greenhouse gas (GHG) emissions and increase food availability for growing populations.

Indigenous Communities

North American non-Indigenous, fossil fuel–based societies can benefit from understanding how Indigenous communities manage carbon in day-to-day living. These communities offer potentially valuable lessons on how to address emissions reduction and carbon capture through people-focused approaches that couple technological and ecological systems with their traditional practices of agrarian-based infrastructure and tribal community values. While quantitative analysis of these practices is only beginning, many Indigenous communities across the United States, Canada, and Mexico are managing carbon stocks and fluxes to reduce GHG emissions through sustainable management of forests, agriculture, and natural resources.

Box 3. How Can SOCCR2 Inform Decision Making?

The information in the *Second State of the Carbon Cycle Report* (SOCCR2) reflects the current peer-reviewed, scientific consensus of the multidisciplinary carbon cycle research community. This decadal assessment responds to the needs of multiple stakeholder groups that rely on the science it encompasses to manage ecosystem services and prioritize actions for reducing carbon emissions, as these groups aim to mitigate the effects of climate change on their communities and environments. Stakeholders in governments and institutions at the federal, provincial, state, and local levels, as well as carbon registries, utilities, and corporations, can use SOCCR2 information to better inform management strategies and options for transportation systems, critical infrastructure, land and ecosystem management, and other decisions that are sensitive to carbon cycle changes.

Cities and Carbon

Urban areas in North America are the primary source of anthropogenic carbon emissions. Emissions from the urban built environment are directly shaped by societal factors, including regulations and policies governing land use, technologies such as transportation, and indirect factors such as demands for goods and services produced outside city boundaries. Such societal drivers can lock in dependence on fossil fuels in the absence of major technological, institutional, and behavioral change. In urban areas many pivotal decisions and policies are made that shape carbon fluxes and mitigation (see Box 3, How Can SOCCR2 Inform Decision Making?, this page).

Knowledge Gaps and Science Informing Investments in the Future

Future research will facilitate improvements in knowledge, practices, and technologies for managing carbon emissions, removing carbon from the atmosphere, and accumulating and storing it in Earth systems over the long term. Expansions in monitoring, advanced syntheses of available observations, improvements in assessment tools and models, and extension of existing modeling capabilities can help provide more reliable measurements and future estimates of carbon stocks and flows at the local, regional, and global level. Co-benefits, such as improvements in air quality, crop productivity, energy efficiency, economic savings to taxpayers, and enhanced quality of life, often result from reduction in carbon emissions. Research identifying and responding to such opportunities—as well as addressing needs for research in carbon management and emissions mitigation across decision-making stakeholders, sectors, and governance at multiple levels—is an investment in the sustainable well-being of Earth, society, and future generations.

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Preface

About This Report

The *Second State of the Carbon Cycle Report* (SOCCR2), a special interagency "highly influential scientific assessment," is led and developed by the Carbon Cycle Interagency Working Group (CCIWG) under the auspices of the U.S. Global Change Research Program (USGCRP).[1] Contributing to the congressionally mandated *Fourth National Climate Assessment* (NCA4), SOCCR2 is a USGCRP Sustained Assessment Product focused on advances in the science and understanding of the carbon cycle across North America since the *First State of the Carbon Cycle Report* (SOCCR1; CCSP 2007). Specifically, SOCCR2 focuses on U.S. and North American carbon cycle processes, stocks, fluxes, and interactions with global-scale carbon budgets and climate change impacts in managed and unmanaged systems (see Box P.1, Carbon Cycle Terminology and Reporting Units, p. 6). The report includes an assessment of carbon stocks and fluxes in urban areas, agriculture, human settlements, the atmosphere, forests, grasslands, Arctic ecosystems, soils, and aquatic systems (wetlands, estuaries, and the coastal ocean). It considers relevant carbon management science perspectives and science-based tools for supporting and informing decisions, as addressed in and related to the publication titled *A U.S. Carbon Cycle Science Plan* (Michalak et al., 2011). SOCCR2 also is aligned with 1) the USGCRP Strategic Plan 2012–2021 (USGCRP 2012); 2) the 2017 USGCRP Triennial Update to the Strategic Plan (USGCRP 2017a), including the "Goal 3: Conduct Sustained Assessments" content therein; and 3) the Global Change Research Act (1990). SOCCR2 provides a status of measurements, observations, and projections of carbon stocks and fluxes, identifying their uncertainties and emerging opportunities for improvements.

Intended Audience

SOCCR2 is intended for a diverse audience that includes scientists; decision makers in the public and private sectors; and communities across the United States, North America, and the world. Overall, this is a scientific, technical report written to inform both expert and nonexpert users. It includes an Executive Summary, p. 21, that is also technical but designed for a somewhat broader, more general audience. This report provides updated information on the observed status and trends in the carbon cycle as influenced by natural and anthropogenic changes. It also informs policies but does not prescribe or recommend them. In this respect, SOCCR2 helps inform mitigation and adaptation policies and management decisions related to the carbon cycle, supporting improved coordination for pertinent research, monitoring, and management activities for responding to global change.

USGCRP's Sustained Assessment Process and the National Climate Assessment

SOCCR2 has been developed as part of the U.S. Global Change Research Program's Sustained Assessment[2] process. This process facilitates continuous and transparent participation of scientists and stakeholders across regions and sectors, enabling the synthesis of new information and insights as they emerge. As a Sustained Assessment process

[1] The U.S. Global Change Research Program (USGCRP) comprises representatives from 13 federal departments and agencies of the United States that conduct research and support the nation's response to global change. It is overseen by the Subcommittee on Global Change Research of the National Science and Technology Council's Committee on Environment, which in turn is overseen by the White House Office of Science and Technology Policy. Agencies working within USGCRP are the U.S. Department of Agriculture, U.S. Department of Commerce, U.S. Department of Defense, U.S. Department of Energy, U.S. Department of Health and Human Services, U.S. Department of the Interior, U.S. Department of State, U.S. Department of Transportation, U.S. Environmental Protection Agency, National Aeronautics and Space Administration, National Science Foundation, Smithsonian Institution, and U.S. Agency for International Development.

[2] www.globalchange.gov/what-we-do/assessment/sustained-assessment

Box P.1 Carbon Cycle Terminology and Reporting Units

Sources, Sinks, and Transfers

When discussing carbon reservoirs and movement of carbon among them, the carbon balance (or budget) is often described relative to the atmosphere as either a "source" or a "sink." Referring to a reservoir (e.g., inland waters) as a "source" means that, after assessing the many different fluxes of carbon (e.g., photosynthesis and respiration), overall there is more carbon moving from the reservoir into the atmosphere than there is moving from the atmosphere into the reservoir. When a reservoir (e.g., a forest) is denoted as a "sink," the opposite is true; there is more carbon moving from the atmosphere into the reservoir than is being released from the reservoir to the atmosphere. By convention, sources and sinks are assigned either positive or negative signs. A positive number is used for sources because they add carbon to the atmosphere, while negative numbers are given for sinks because they remove carbon from the atmosphere. "Transfers," which also may be referred to as "lateral transfers" or "redistributions," indicate movement of carbon between land and water classes with little or no exchange with the atmosphere. Thus, these transfers are neither sources nor sinks but must be considered in the carbon balance of specific domains, particularly inland waters and export of carbon forms to the coastal ocean. See Appendix G: Glossary, p. 851, for additional terminologies and definitions.

Reporting Units

In discussions about amounts of carbon in pools, levels of carbon are denoted as teragrams (Tg) or petagrams (Pg) of carbon (C), and fluxes are denoted in Tg C per year or Pg C per year. Units are defined below, along with their common equivalents typically used in carbon flux reporting:

- Teragram (Tg): A unit of mass equal to 10^{12} grams (g) = 1 million metric tons = Mt (megaton)
- Petagram (Pg): A unit of mass equal to 10^{15} g = 1 billion metric tons = Gt (gigaton)
- Petagrams of carbon (Pg C) = gigaton of carbon (Gt C)
- Teragrams of carbon (Tg C) = million metric tons of carbon (MMT C) = megaton of carbon (Mt C)
- Tg C = 10^{12} g = 10^6 tons
- Conversion of carbon to carbon dioxide (CO_2): Multiply the mass of carbon by 3.67 based on the relative molecular weights of carbon and oxygen.
- Carbon dioxide equivalent (CO_2e): Amount of CO_2 that would produce the same effect on the radiative balance of Earth's climate system as another greenhouse gas, such as methane (CH_4) or nitrous oxide (N_2O). Typically, CO_2e is calculated over a specified time period (e.g., 100 years) when comparing different gases. For comparison to units of carbon, each kg CO_2e is equivalent to 0.273 kg C (0.273 = 1 ÷ 3.67). For more information, see Box P.2, Global Carbon Cycle, Global Warming Potential, and Carbon Dioxide Equivalent, p. 12.
- Methane is usually represented in this report in units of Tg CH_4, though sometimes in units of Tg CH_4-C when methane is an important component of a system's carbon budget (as in the case of terrestrial wetlands).

report, SOCCR2 provides a comprehensive assessment of the science and associated human dimensions of carbon cycling in land, air, and water, with a focus on the United States and North America in a global context. SOCCR2 contributes to and informs the congressionally mandated National Climate Assessment (NCA) process of the Global Change Research Act (1990). The report also updates the carbon cycle science presented in the *Third National Climate Assessment* (NCA3; Melillo et al., 2014)

and provides the authors of the forthcoming NCA4 Vol. II with additional consensus-based carbon cycle knowledge to bolster their own assessment of the impacts and risks posed by climate change across regions and sectors of the United States. The USGCRP assessment reports together cover sectors and topics (see Table P.1, p. 8) mandated by the Global Change Research Act (1990), responding to Section 106 on Scientific Assessments by:

1. Integrating, evaluating, and interpreting USGCRP findings and discussing the scientific uncertainties associated with such findings;
2. Analyzing the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and
3. Analyzing current trends in global change, both human induced and natural, and projecting major trends for the next 25 to 100 years.

Sources Used in This Report

The findings in SOCCR2 are based on a large body of scientific, peer-reviewed research, as well as a number of other publicly available sources, including well-established and carefully evaluated observational and modeling datasets. The team of authors carefully reviewed approximately 3,000 such sources to ensure a reliable assessment of the state of scientific understanding. Each source of information was determined to meet the four parts of the Information Quality Act (OMB 2002): 1) utility, 2) transparency and traceability, 3) objectivity, and 4) integrity and security. Report authors assessed and synthesized information from peer-reviewed journal articles, technical reports produced by governmental and non-governmental agencies, scientific assessments (e.g., CCSP 2007; IPCC 2013; Melillo et al., 2014), reports of the National Academies of Sciences, Engineering, and Medicine (NASEM) and its associated National Research Council, various conference proceedings, and governmental statistics from North American and global sources.

Report Development, Review, and Approval Process

SOCCR2 is a U.S. government interagency product of the U.S. Global Change Research Program. This assessment is organized, led, and overseen by the following member agencies of the Carbon Cycle Interagency Working Group, which leads the U.S. Carbon Cycle Science Program:

- National Aeronautics and Space Administration (NASA)
- National Science Foundation (NSF)
- U.S. Agency for International Development (USAID)
- U.S. Department of Agriculture (USDA), including the Forest Service, National Institute of Food and Agriculture, Agricultural Research Service, Economic Research Service, and Natural Resources Conservation Service
- U.S. Department of Commerce, including the National Institute of Standards and Technology (NIST) and the National Oceanic and Atmospheric Administration (NOAA)
- U.S. Department of Energy (DOE)
- U.S. Department of the Interior, including the U.S. Geological Survey (USGS)
- U.S. Environmental Protection Agency (EPA)

A Federal Steering Committee, composed of a subset of the CCIWG and its member departments and agencies, was established in early 2015 to develop a Prospectus[3] to guide SOCCR2 and provide regular guidance to authors. USDA served as the federal administrative lead for this report (see Appendix A: Report Development Process, p. 810).

The process for preparing SOCCR2 is consistent with the guidelines for preparing USGCRP products, with referenced materials derived primarily

[3] www.carboncyclescience.us/sites/default/files/cciwg/SOCCR-2Prospectus-March-15-2017-FINAL-2.pdf

Table P.1. Examples of SOCCR2 Chapters with Topics Related to NCA4 Vol. II Chapters[a]

SOCCR2 Sections	No.	SOCCR2 Chapters	Examples of Pertinent NCA4 Vol. II Chapters
		Highlights	
		Preface: About This Report	
		Preface: Guide to Report	
		Preface: Interagency Context of U.S. Carbon Cycle Science	
		Executive Summary	
I: Synthesis	1	Overview of the Global Carbon Cycle	Our Changing Climate, Complex Systems, Adaptation, Mitigation
	2	The North American Carbon Budget	Adaptation, Mitigation, Land
II: Human Dimensions of the Carbon Cycle	3	Energy Systems	Mitigation, Energy, Transportation, Regions (including Southwest)
	4	Understanding Urban Carbon Fluxes	Built Environment
	5	Agriculture	Agriculture and Rural
	6	Social Science Perspectives on Carbon	Ecosystems, Land, International
	7	Tribal Lands	Tribal and Indigenous, Land
III: State of Air, Land, and Water	8	Observations of Atmospheric Carbon Dioxide and Methane	Our Changing Climate, Air Quality
	9	Forests	Forests, Regions (including Southwest)
	10	Grasslands	Ecosystems, Land
	11	Arctic and Boreal Carbon	International, Alaska
	12	Soils	Ecosystems, Land
	13	Terrestrial Wetlands	Ecosystems, Water
	14	Inland Waters	Ecosystems, Water
	15	Tidal Wetlands and Estuaries	Ecosystems, Oceans, Coastal
	16	Coastal Ocean and Continental Shelves	Coastal Effects, Oceans, International, Regions
IV: Consequences and Ways Forward	17	Biogeochemical Effects of Rising Atmospheric Carbon Dioxide	Mitigation, Air Quality, Oceans
	18	Carbon Cycle Science in Support of Decision Making	Adaptation, International
	19	Future of the North American Carbon Cycle	Our Changing Climate, International

Notes

a) SOCCR2, *Second State of the Carbon Cycle Report*; NCA4, *Fourth National Climate Assessment*.

from the existing, peer-reviewed scientific literature and consistent with USGCRP guidance regarding use of grey literature (see Appendix B: Information Quality in the Assessment, p. 818). Because SOCCR2 is a USGCRP Sustained Assessment report and contributes to NCA4, many of its author guidelines are consistent with or directly derived from those for NCA3 (Melillo et al., 2014) and two other Sustained Assessment reports: *The Impacts of Climate Change on Human Health in the United States* (USGCRP 2016) and *Climate Science Special Report: Fourth National Climate Assessment, Volume I* (USGCRP 2017b). The guidance documents for NCA3 and the *Climate Science Special Report* were made available to the U.S. Carbon Cycle Science Program Office at the beginning of SOCCR2 development in early 2015, were adapted to the specific context of this effort, and used to develop the SOCCR2 Prospectus, which was approved by the Subcommittee on Global Change Research (SGCR) in May 2015. Following a Federal Register Notice for author nominations, technical input, and comments on the SOCCR2 Prospectus in February 2016, the CCIWG selected lead authors for 19 chapters and more than 100 additional contributing authors. This writing team comprises scientists and technical experts representing national laboratories; government agencies; universities; and the private sector across the United States, Canada, and Mexico. Additional contributing authors were chosen later to provide special input on select areas of the assessment. Also selected was a team of five Science Leads from U.S. agencies, national laboratories, and academia to provide high-level scientific expertise and assistance and to ensure consistency in scientific information throughout the report. Drawing from the CCIWG members, one to two Federal Liaisons were assigned to each chapter to review and provide guidance within their area of expertise and pertinent federal research or programmatic portfolio. Further details on the SOCCR2 development processes, timeline, and team roles and responsibilities are provided in Appendix A: Report Development Process, p. 810.

Multiple formal and internal reviews of consecutive SOCCR2 drafts have taken place (see Figure P.1, p. 10), including the following six reviews.

1. Interagency review of the "Second Order Draft" by the SGCR (November 8–23, 2016).
2. Interagency review of the "Third Order Draft" by the SGCR (June 23 to July 21, 2017).
3. NASEM committee review of the "Fourth Order Draft" (November 3, 2017, to March 12, 2018).
4. Public comment period for the "Fourth Order Draft" (November 3, 2017, to January 12, 2018).
5. Iterative internal reviews of multiple drafts by the CCIWG, SOCCR2 Federal Steering Committee members, five Science Leads, SOCCR2 Chapter Leads, Expert Reviewers, Oak Ridge National Laboratory (ORNL) technical editors, and federal experts from different agencies (September 2016 to July 2018). For example, prior to the "Third Order Draft" review by the SGCR, several additional layers of input, reviews, and revisions (February to May 2017) were provided by 1) USDA (i.e., the administrative agency lead for SOCCR2), 2) SOCCR2 Federal Liaisons, 3) external Expert Reviewers, 4) USGCRP leadership, and 5) SOCCR2 writing teams.
6. Following the public comment period and a formal review by NASEM experts, the writing team further revised the report in coordination with Review Editors who were selected via an open call to ensure appropriate responses to comments. The draft was subsequently reviewed and approved for final publication by USGCRP member agencies as part of the interagency clearance process: Final Interagency Clearance of the "Fifth Order Draft" by the SGCR (July 31 to August 20, 2018).

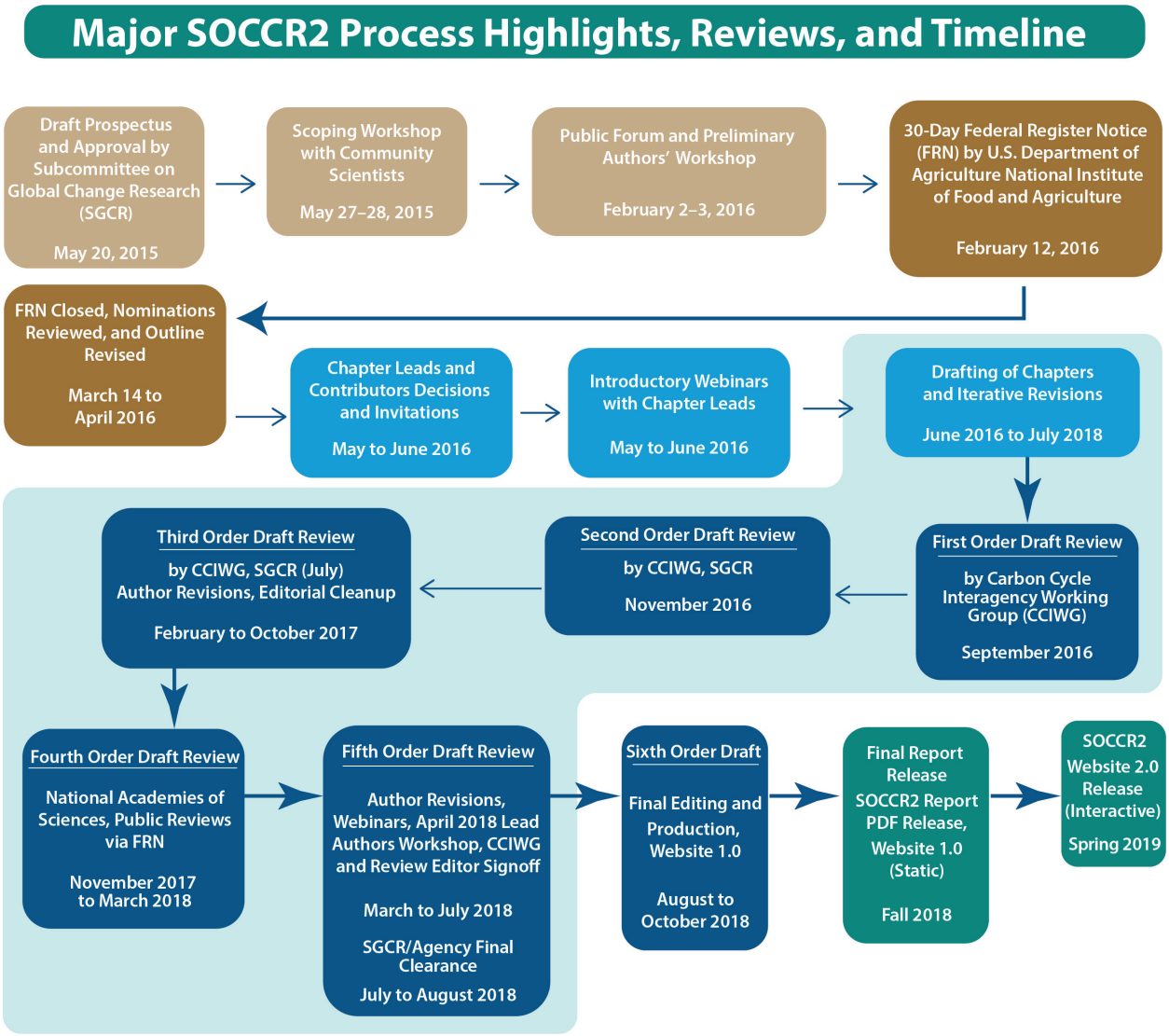

Figure P.1. Major SOCCR2 Process Highlights, Reviews, and High-Level Timeline. Brown boxes denote foundational, developmental stages in the process. Dark blue boxes denote drafting, review, and revision stages.

Guide to the Report

Scientific Framing of the Report

SOCCR2's focus areas and guiding questions were inspired by the community-led report entitled *A U.S. Carbon Cycle Science Plan* (Michalak et al., 2011), whose goals and emphasis include global-scale research on long-lived, carbon-based greenhouse gases (GHGs), mainly carbon dioxide (CO_2) and methane (CH_4)[4], and the major pools and fluxes of the global carbon cycle. Further bolstering the science plan goals, SOCCR2 has a greater emphasis on the United States and North America within a global context:

1. How have natural processes and human actions affected the global carbon cycle on land, in the atmosphere, in the ocean and other aquatic systems, and at ecosystem interfaces (e.g., coastal, wetland, and urban-rural)?
2. How have socioeconomic trends affected atmospheric levels of the primary carbon-containing gases, CO_2 and CH_4?
3. How have species, ecosystems, natural resources, and human systems been impacted by increasing GHG concentrations, associated changes in climate, and carbon management decisions and practices?

Note that U.S. federal GHG inventories are the responsibilities of several federal agencies. SOCCR2 does not seek to evaluate, critique, or validate those inventories but rather to explore and present the current state of the science of the carbon cycle. Any discussions of current U.S. GHG inventories are conducted within the broader context of the carbon cycle. Where there are any apparent discrepancies with U.S. GHG inventories, or where otherwise appropriate, SOCCR2 explains or identifies the different sources of the discrepancies.

[4] Methane has an intermediate atmospheric lifetime (estimated between 8 and 13 years) and thus is sometimes categorized as short-lived, though the Intergovernmental Panel on Climate Change and the U.S. Environmental Protection Agency classify methane as long-lived. Its actual lifetime depends on atmospheric chemistry and other conditions.

Framing of Report

SOCCR2 is framed around the following topics:

1. **Global Carbon Cycle Overview**—Major elements of the global carbon cycle (e.g., CO_2 and CH_4,) and key interactions with climate forcing and feedback components from a global perspective (see Box P.2, Global Carbon Cycle, Global Warming Potential, and Carbon Dioxide Equivalent, p. 12).
2. **Carbon Cycle at Scales**—Assessment of the North American carbon cycle (scaled down from the global system), including short- to long-term and local, regional, and national perspectives on key carbon stocks and fluxes.
3. **Carbon in Unmanaged and Managed Systems**—Estimates and assessment of major carbon stocks and fluxes within and among pools, key uncertainties, social drivers, and effects of past management decisions. Example focus areas include:
   - Urban and human settlements;
   - Livestock and wildlife;
   - Soils;
   - Aquatic systems; and
   - Vegetation.
4. **Interactions and Disturbance Impacts to the Carbon Cycle**—Role of disturbances on the carbon cycle, for example:
   - Fires;
   - Ocean acidification;
   - Pests and diseases of ecosystem components; and
   - Land-use change and land-cover change.
5. **Carbon Cycle Management Practices, Tools, and Needs at Various Scales:**
   - Role of recent carbon management practices;
   - Current state of carbon data management;
   - Monitoring systems;
   - Tools;
   - Carbon-relevant modeling scenarios; and
   - Mitigation.

Box P.2 Global Carbon Cycle, Global Warming Potential, and Carbon Dioxide Equivalent

Greenhouse gases (GHGs)—including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)—are released during both natural and anthropogenically mediated carbon cycling and are part of the tight coupling of the carbon and nitrogen cycles in ecosystems. Because these gases have different radiative efficiencies and atmospheric residence times, comparing their relative effects on climate requires a metric. Radiative effects are compared using various metrics such as the global temperature change potential (GTP) for assessing instantaneous impacts, or the global warming potential (GWP) for assessing impacts integrated over time; the intricacies of the comparison techniques differ depending on the metric. The most widely used climate metric, GWP, evaluates the cumulative forcing of a 1-kg pulse emission of a particular GHG over a specified analytical time horizon, and then it normalizes against that of a 1-kg pulse emission of CO_2 evaluated over the same time horizon. Multiplying this value (the GWP) by the GHG emission yields the CO_2 equivalent (CO_2e)—the amount of CO_2 that would have the same warming effect over that time period as the amount of the particular GHG emitted.

The Intergovernmental Panel on Climate Change (IPCC) has evaluated GWP over 20- and 100-year analytical time horizons (denoted by GWP_{20} and GWP_{100}, respectively; Myhre et al., 2013). These assessments are indicators of climate effects in the near- and long-term, respectively. Wherever this report presents CO_2e results, such as in Ch. 3: Energy Systems and except where noted otherwise, the results refer to the IPCC GWP_{100} values (without consideration of indirect effects and feedbacks). This semi-arbitrary but common choice of the 100-year analytical time horizon tends to de-emphasize the near-term climate impacts of CH_4 and other short-lived climate forcers. Although best practices call for reporting GWP_{20} and GWP_{100} values together as a pair (Ocko et al., 2017) or using temporally explicit climate impact accounting that avoids the issue of time horizon altogether (Alvarez et al., 2012), most of the previous studies available to inform this report evaluated climate impacts on a GWP_{100} basis only. Also, while these CO_2e estimates reflect several of the most important GHGs related to global carbon cycling, they stop short of a full climate impact accounting. Aerosols and black carbon emissions are significant climate forcers important in some natural processes and energy-use pathways (e.g., traditional biomass combustion), though translating them to CO_2e terms is very difficult because of their short atmospheric residence times (i.e., about a week) and thus high regional variability complicated by local interactions with clouds and surface snow and ice. This difficulty results in GWP values with high uncertainty ranges (Myhre et al., 2013) and makes a global value inappropriate. Likewise, albedo changes and other biophysical changes are significant in certain land-management settings (Caiazzo et al., 2014) but also are challenging to express simply in GWP terms for similar reasons.

Author Guidance and Chapter Organization

To ensure consistency throughout SOCCR2 with regard to methods, approaches, and considerations of scientific quality, an author guidance document was developed, in consultation with USGCRP, by the SOCCR2 planning team (Federal Steering Committee, the U.S. Carbon Program Office, and Science Leads), along with the ORNL technical editing team. Formal guidance on Information Quality was also provided (see Appendix B: Information Quality in the Assessment, p. 818). The author guidance established a recommended methodology and chapter structure (including templates) for composing the chapters as described below. In some cases, the chapter structure or template was modified by the authors, as appropriate, based on a chapter's specific relevance to the structure and information type (e.g., Ch. 6: Social Science Perspectives on Carbon, p. 264).

1. **Introduction**—Summarizes the topic of the chapter, specifying the key questions needed to understand and quantify the carbon cycle. Spatial and temporal scales relevant to the chapter are described.

2. **Historical Context**—Summarizes the history of carbon stock and flux quantification with regard to the spatiotemporal scope of the chapter. Historical context includes socioeconomic drivers of carbon emissions (where appropriate), along with an introduction to the use of different approaches and their evolution over time, particularly focusing on findings that have emerged since SOCCR1 (CCSP 2007).

3. **Current Understanding of Carbon Fluxes and Stocks**—Discusses the "state of the science" in terms of conceptually understanding, measuring, quantifying, and modeling the carbon cycle at the spatiotemporal scale of the chapter. As appropriate, this section describes different methodologies used in research activities and mentions the various assumptions and caveats for each approach (see Appendix C: Selected Carbon Cycle Research Observations and Measurement Programs, p. 821).

4. **Indicators, Trends, and Feedbacks**—Describes the exact observed indicators and trends of the carbon cycle at the spatiotemporal scale of the chapter. This includes understanding of the extent of agreement or disagreement between presumed trends, pre- and post-2007 (if applicable). The section also summarizes feedbacks among different ecosystem compartments or pools of Earth System Models or process models. Feedbacks to one ecosystem compartment may provide critical input to another compartment, for example, or from one spatial scale to another.

5. **Global, North American, and Regional Context**
   - **National Climate Assessment (NCA) 2014 and 2018 regions**—Places carbon processes, stocks, and fluxes at a particular scale in the chapter in the context of NCA regions, which are reflective of the scale at which physical and environmental processes operate. NCA regions also could be considered "actionable" by policymakers. The NCA 2014 regions consist of Northeast, Southeast, Midwest, Great Plains, Southwest, Northwest, Alaska, Hawai'i, and United States–Affiliated Pacific Islands, Rural Communities, and Coasts. NCA 2018 splits the Great Plains region into the Northern Great Plains and Southern Great Plains and divides the Caribbean and Southeast into separate regions.
   - **United States, Mexico, and Canada**—Places carbon processes, stocks, and fluxes at a particular scale in the chapter in the context of North America and the planet, scales at which most Earth System Models operate. When available, country-level information also is presented because it is at a scale that policymakers could consider actionable.

6. **Societal Drivers, Impacts, and Carbon Management Decisions**—Focuses on observed and projected impacts of changes in or to the carbon cycle for the ecosystems being considered.

Also described are societal costs of the impacts, including economics. Information about carbon management decisions is intended to summarize the impacts of past decisions (if applicable), evaluate the efficacy of those decisions regarding their intended consequence, and highlight techniques for determining the effects of decisions on the targeted system. The section also could pose relevant scientifically based carbon management concepts as summarized from the literature.

7. **Synthesis, Knowledge Gaps, and Outlook**—Provides an overarching synthesis of the current state of the carbon cycle, describes knowledge gaps and opportunities, and discusses the near-term future outlook of the North American carbon cycle. Although the goal of SOCCR2 is to highlight and synthesize the current state of the science on carbon cycling in North America, the research needs and critical scientific gaps identified through the development of each chapter and described in this section may serve to inform ongoing and future studies by the scientific community.

Geographical Scope

The major focus of SOCCR2 is North America, with an emphasis on the United States. This emphasis is consistent with the report's purpose of providing solid scientific information to 1) U.S. decision makers and policymakers that could be used to formulate activities or policies, 2) the scientific community, and 3) teachers for educational use in the classroom. Because the effects of carbon cycle changes are global-scale issues, SOCCR2 addresses carbon cycling from a global perspective, where appropriate. Moreover, since SOCCR2 seeks to be consistent with SOCCR1 (CCSP 2007), which focused on North America, chapters also consider the carbon cycle in Canada and Mexico. Regional-scale discussions may be included where appropriate. The geographical scope of U.S. analysis for SOCCR2 includes the conterminous United States, Alaska, Hawai'i, and Puerto Rico. U.S. regional studies, if included, are presented where processes and impacts vary significantly across the nation and where regional information is available (see Figure ES.1, p. 23, in the Executive Summary).

Time Frames

Assessing the balance of respective sources and sinks within the Earth system and the atmosphere is complicated by many factors. Exchanges of carbon among different reservoirs can occur in different time frames, with some reservoirs having very dynamic fluxes and responding almost instantaneously to change and other reservoirs having fluxes that are driven by controls that work on much longer timescales of decades to centuries. SOCCR2 is focused on a time frame relevant to understanding and predicting the carbon cycle and the effects of changes to the carbon cycle now and into the near future. The U.S. Global Change Research Act of 1990 mandates a scope of 25 years and 100 years from present day. As appropriate, SOCCR2 describes the relevant timescales, with retrospective estimates mostly representing the decade since SOCCR1 (i.e., 2004 to 2013) and projections involving time frames of decades to a century.

The emphasis is on presenting the scientific understanding and developments that have emerged in the last decade since SOCCR1 (CCSP 2007), which covered the science through 2005. The historical context may go farther back, as appropriate, considering the data sources and the need to set the historical context. Model simulations may begin with preindustrial or geological time frames to converge with current estimations of carbon stocks or concentrations and landscape configuration, for example. For literature data and reviews, the time frame may vary depending on the focus of the relevant literature or model simulations. Chapters or sections describing the impacts of changes to the carbon cycle, mitigation plans, or adaptive strategies also may pose future scenarios.

SOCCR2 summarizes the latest science in North America, using time frames that may differ from ones used for inventories (e.g., U.S. EPA Inventory). For example, inventories are updated regularly, and

scenarios used in analyses and related to the policies and politics of climate change and GHG emissions are rapidly changing. On the other hand, research investigations to understand and explain fluxes and changes in both ecological and social contexts often take many years. Time frames also were based on the latest available and comparable carbon cycle data for all three SOCCR2 countries when assessed together. For instance, Ch. 8: Observations of Atmospheric Carbon Dioxide and Methane, p. 337, selected the Carbon Dioxide Information Analysis Center (CDIAC) time series to represent fossil fuel emissions from Canada, the United States, and Mexico from 2004 to 2013 because of CDIAC's long historical coverage for all three countries for that time frame and for the clear definition of what goes into the country totals (Marland et al., 2007).

Complex Linkages and the Role of Non-Climate Stressors

Multiple factors, including climate, may exacerbate or moderate the impact of changes to the carbon cycle on ecosystems, processes, and society, as well as potential feedbacks from these changes to the climate system. For example, the history of land-use change, natural climate variability, landscape-scale heterogeneity, anthropogenic effects, and more may affect an ecosystem's vulnerability to carbon cycle changes and the vulnerability of its carbon pools to changes in climate. Many of these complex interactions and cascading effects are not well understood and thus not entirely addressed in SOCCR2.

Frameworks for Carbon Accounting

Two approaches to quantify carbon cycle components inform research and analysis for scientific studies, and for management and decisions: "production-based" and "consumption-based" accounting. These approaches provide different insights and inform different stakeholder interests and management decisions. To satisfy the requirement for numerical coherence throughout analyses of the carbon cycle in North America, SOCCR2 predominantly uses a production-oriented approach. The production-based or "in-boundary" accounting considers flows of CO_2 and CH_4 into and out of specific areas of land or water. For a hectare of land, net emissions result from, for example, photosynthesis, absorption of CO_2 by concrete, combustion of fossil fuel at a power plant, and the decay of plants and animals on that parcel. In practice, analyses of terrestrial ecosystems such as forests and grasslands also typically include lateral transfers of carbon among parcels (e.g., via erosion or streamflow). The other accounting approach, consumption-based accounting, assigns carbon flows associated with products and services (e.g., timber, electricity, food, chairs, televisions, and heat) to the places where people ultimately use those products. This approach captures demand and trade as drivers of carbon emissions. Emissions from fossil fuel combustion to produce electricity are assigned not to a power plant but to the places where people use that electricity; emissions from crop production are assigned to the place where food is consumed (by humans or animals); carbon captured in trees harvested for timber is assigned to the timber mill or to the place where the timber is used. Quantification of these indirect fluxes typically uses a life cycle assessment framework and also can quantify the carbon stock residing in infrastructure and materials. See Appendix D: Carbon Measurement Approaches and Accounting Frameworks, p. 834, for a more complete description of carbon accounting approaches and their implications.

Methods for Estimating Carbon Stocks and Fluxes

The SOCCR2 author teams assessed research findings based on three observational, analytical, and modeling methods to estimate carbon stocks and fluxes: 1) inventory measurements or "bottom-up" methods, 2) atmospheric measurements or "top-down" methods, and 3) ecosystem models (see Appendix D, p. 834, for details). "Bottom-up" estimates of carbon exchange with the atmosphere depend on measurements of carbon contained in biomass, soils, and water, as well as measurements of CO_2 and CH_4 exchange among the land, water, and atmosphere. Examples include direct measurement

of power plant carbon emissions; remote-sensing and field measurements repeated over time to estimate changes in ecosystem stocks; measurements of the amount of carbon gases emitted from land and water ecosystems to the atmosphere (in chambers or, at larger scales, using sensors on towers); and combined urban demographic and activity data (e.g., population and building floor areas) with "emissions factors" to estimate the amount of CO_2 released per unit of activity.

Top-down approaches infer fluxes from the terrestrial land surface and ocean by coupling atmospheric gas measurements (using air sampling instruments on the ground, towers, buildings, balloons, and aircraft or remote sensors on satellites) with carbon isotope methods, tracer techniques, and simulations of how these gases move in the atmosphere. The network of GHG measurements, types of measurement techniques, and diversity of gases measured has grown exponentially since SOCCR1 (CCSP 2007), providing improved estimates of CO_2 and CH_4 emissions and increased temporal resolution at regional to local scales across North America.

Ecosystem models are used to estimate carbon stocks and fluxes with mathematical representations of essential processes, such as photosynthesis and respiration, and how these processes respond to external factors, such as temperature, precipitation, solar radiation, and water movement. Models also are used with top-down atmospheric measurements to attribute observed GHG fluxes to specific terrestrial or ocean features or locations.

Treatment of Uncertainty in SOCCR2

Uncertainty in estimates of values in this report is based on standards established in SOCCR1 (CCSP 2007) and NCA3 (Melillo et al., 2014). The notations and definitions of uncertainty described in this section pertain primarily to reported estimates of carbon stocks and fluxes that are based on statistical sampling or other analytical approaches for which uncertainty can be quantitatively or qualitatively assessed.

In many (if not most) cases, a quantitative statistical uncertainty estimate does not exist for all available numerical values from the literature, so deducing the level of uncertainty using an expert opinion approach is necessary. If quantitative uncertainty estimates are not available, reported uncertainty levels are based on the expert assessment and consensus of the author team. The authors determine the appropriate level of uncertainty by assessing the available literature, determining the quality and quantity of available evidence, and evaluating the level of agreement across different studies. When the underlying studies provide their own estimates of uncertainty and confidence intervals, these confidence intervals are assessed by the authors in making their own expert judgments. A range of estimates may be presented in cases where there are multiple estimates available from different sources or methodologies. For example, estimating the magnitude of the North American terrestrial carbon sink is possible using several approaches: compiled inventories, atmospheric inversions, or modeling that may be informed by remote sensing. It is not practical to quantitatively estimate uncertainty when combining such estimates to derive a single value, in which case a single value may be estimated using expert opinion, or a range of values without also showing a quantitative uncertainty estimate.

Estimating Ranges of Quantitative Values

Unless otherwise noted, values presented as "$y \pm x$" should be interpreted to signify that the authors are 95% confident that the actual value is between $y - x$ and $y + x$. The 95% boundary was chosen to communicate the high degree of certainty that the actual value is in the reported range and the low likelihood (5%) that it is outside that range. This range may reflect a statistical property of the estimate or, more likely, expert judgment based on all known published descriptions of uncertainty surrounding the "best available" or "most likely" estimate.

Uncertainty of Numerical Estimates

In many tables and figures, a series of asterisks is used to express the uncertainty of numerical

estimates (which may be based on statistical properties or expert judgment):

1. ***** — **Very high confidence** (95% certain that the actual value is within 10% of the estimate reported).
2. **** — **High confidence** (95% certain that the actual value is within 25% of the estimate reported).
3. *** — **Medium confidence** (95% certain that the actual value is within 50% of the estimate reported).
4. ** — **Low confidence** (95% certain that the actual value is within 100% of the estimate reported).
5. * — **Very low confidence** (uncertainty greater than 100%).

Key Findings and Supporting Evidence

Each chapter includes Key Findings based on the authors' consensus expert judgment of the assessed scientific literature. Each Key Finding is accompanied by a Supporting Evidence section, which includes each Key Finding's "Traceable Account" description. This section and the traceable account 1) provide additional information to readers about the quality of the information used, 2) allow traceability to resources and data, 3) document the process and rationale the authors used in reaching the conclusions in a Key Finding, and 4) describe the confidence level and likelihood in the Key Finding, as appropriate (see Figure P.2, this page). For each Key Finding, authors characterize confidence levels quantitatively when possible, and, when not possible, they rank uncertainty qualitatively by reporting their level of confidence in the results.

Confidence Level	Likelihood
Very High	**Very High**
Strong evidence (established theory, multiple sources, consistent results, well-documented and accepted methods, etc.), high consensus	≥ 9 in 10
	Likely
	≥ 2 in 3
High	**As Likely As Not**
	≈ 1 in 2
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus	**Unlikely**
	≤ 1 in 3
Medium	**Very Unlikely**
	≤ 1 in 10
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought	
Low	
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts	

Figure P.2. Likelihood and Confidence Evaluation.

Interagency Context of U.S. Carbon Cycle Science

"… Carbon-cycling research has been a focus for the U.S. Global Change Research Program (USGCRP) agencies because of the role carbon plays as a major regulator of Earth's climate and as a key factor in controlling the acidity of the global oceans in order to assess and predict change; both carbon fluxes to the atmosphere (sources) and carbon sequestration in land and ocean ecosystems (sinks) need to be understood and quantified. The USGCRP agencies have championed strategic planning activities and promoted and coordinated core observations and process studies on global carbon sources and sinks. In 1998, the Carbon Cycle Interagency Working Group (CCIWG) was formally constituted to coordinate efforts that 12 U.S. government agencies and departments now lead as part of the U.S. Carbon Cycle Science Program. During the past 25 years, research organized and supported in part by the USGCRP has greatly increased our understanding of the processes involved in, for example, the potential for enhanced decomposition of soil carbon as the climate warms, and the processes influencing carbon dioxide uptake in a warming ocean. Important components of this research are intensive, interagency coordinated field campaigns that unite in-situ, air-borne, and satellite-based observations…."

—U.S. National Academies of Sciences, Engineering, and Medicine 2017

Established more than 27 years ago following the authorization of the Global Change Research Act of 1990 by the U.S. Congress, the U.S. Global Change Research Program (USGCRP) alliance of 13 U.S. governmental agencies and departments leads and facilitates federal research coordination to implement the mandate of the Global Change Research Act. This legal mandate requires that USGCRP assist the nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change. Interagency working groups and task teams have been an integral aspect of USGCRP's evolution, implementing its annual priorities and decadal strategic goals (see Box P.3, Maximizing Interagency Coordination, this page). The Carbon Cycle Interagency Working Group (CCIWG), established in 1998, is the longest-running USGCRP interagency working group. Its goals, objectives, functions, and activities, along with those of the U.S. Carbon Cycle Science Program (established in 1999), align with the goals of the decadal USGCRP strategic plans (e.g., USGCRP

Box P.3 Maximizing Interagency Coordination

The U.S. Fiscal Year 2019 Administration Research and Development Budget Priorities Memo (White House 2018) emphasized "Maximizing Interagency Coordination" as one of its three recommended research and development practices for the federal government, stating that "agencies should support ongoing interagency initiatives and participate in applicable interagency coordination groups." Such interagency coordination and collaborations for domestic and global change research were mandated in the Global Change Research Act (1990). The development of the *Second State of the Carbon Cycle Report* (SOCCR2) represents an example of the culmination of such coordination and collaboration in partnership with the North American science community, led and facilitated by the Carbon Cycle Interagency Working Group (CCIWG) and the U.S. Carbon Cycle Science Program under the auspices of the U.S. Global Change Research Program (USGCRP). SOCCR2 synthesizes and assesses much of the carbon research that has been supported and coordinated by CCIWG and USGCRP agencies, including facilitation by the CCIWG and the U.S. Carbon Cycle Science Program through interagency cross-disciplinary workshops, scientific investigators' meetings, scientific engagement, formal and informal partnerships, and joint research solicitations.

2012). CCIWG activities and goals are implemented in harmony with those plans and community-based science plans, including *A U.S. Carbon Cycle Science Plan* (Sarmiento and Wofsy 1999; Michalak et al., 2011), and they support new priorities and USGCRP directives, as well as carbon cycle research needs arising from new scientific findings and observations. The U.S. Carbon Cycle Science Program, in consultation with CCIWG, coordinates and facilitates activities relevant to carbon cycle science, climate, and global change issues under the auspices of the Subcommittee on Global Change Research (SGCR). CCIWG supports the peer-reviewed research of carbon cycle science across the federal government and is responsible for defining program goals, setting research priorities, and reviewing the progress of the research programs that contribute to carbon cycle science. CCIWG has sought to better understand past changes and current trends in atmospheric carbon dioxide (CO_2) and methane (CH_4), deliver credible predictions of future atmospheric CO_2 and CH_4 levels, and strengthen the scientific foundation for management decisions in numerous areas of public interest related to carbon and climate change in the United States and other regions. Twelve federal agencies and departments coordinate and support CCIWG program activities. The U.S. Carbon Cycle Science Program, in coordination with the carbon cycle science community, established the North American Carbon Program in 2002 and the Ocean Carbon and Biogeochemistry Program in 2006. Several international activities also have been vital components of the program, including those of CarboNA (i.e., international partnership of Canada, Mexico, and the United States on the North American carbon cycle) and the Global Carbon Project. The mission of the CCIWG and the U.S. Carbon Cycle Science Program is to coordinate and facilitate federally funded carbon cycle research and provide leadership to USGCRP on carbon cycle science priorities. Over the 20 years since its establishment, this partnership continues to respond to community science needs, advances, opportunities, and governmental priorities while also informing pertinent decisions.

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Executive Summary

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Introduction

Central to life on Earth, carbon is essential to the molecular makeup of all living things and plays a key role in regulating global climate. To understand carbon's role in these processes, researchers measure and evaluate carbon stocks and fluxes. A stock is the quantity of carbon contained in a pool or reservoir in the Earth system (e.g., carbon in forest trees), and a flux is the direction and rate of carbon's transfer between pools (e.g., the movement of carbon from the atmosphere into forest trees during photosynthesis). This document, the *Second State of the Carbon Cycle Report* (SOCCR2), examines the patterns of carbon stocks and fluxes—collectively called the "carbon cycle." Emphasis is given to these patterns in specific sectors (e.g., agriculture and energy) and ecosystems (e.g., forests and coastal waters) and to the response of the carbon cycle to human activity. The purpose of SOCCR2 is to assess the current state of the North American carbon cycle and to present recent advances in understanding the factors that influence it. Concentrating on North America—Canada, the United States, and Mexico—the report describes carbon cycling for air, land, inland waters (streams, rivers, lakes, and reservoirs), and coastal waters (see Figure ES.1, p. 23).

The questions framing the publication *A U.S. Carbon Cycle Science Plan* (Michalak et al., 2011) inspired development of three slightly modified questions that guide SOCCR2's content and focus on North America in a global context:

1. How have natural processes and human actions affected the global carbon cycle on land, in the atmosphere, in the ocean and other aquatic systems, and at ecosystem interfaces (e.g., coastal, wetland, and urban-rural)?

2. How have socioeconomic trends affected atmospheric levels of the primary carbon-containing gases, carbon dioxide (CO_2) and methane (CH_4)?

3. How have species, ecosystems, natural resources, and human systems been impacted by increasing greenhouse gas (GHG) concentrations, associated changes in climate, and carbon management decisions and practices?

SOCCR2 synthesizes the most recent understanding of carbon cycling in North America, assessing new carbon cycle findings and information, the state of knowledge regarding core methods used to study the carbon cycle, and future research needed to best inform carbon management and policy options. Focusing on scientific developments in the decade since the *First State of the Carbon Cycle Report* (SOCCR1; CCSP 2007), SOCCR2 summarizes the past, current, and projected state of carbon sources, sinks, and natural processes, as well as contributions by human activities. In addition to CO_2 and CH_4, the report sometimes discusses nitrous oxide (N_2O), a GHG associated with activities and processes that affect fluxes of carbon gases.[1] SOCCR2 also describes improvements in analysis tools; developments in decision support; and new insights into ecosystem carbon cycling, human causes of changes in the carbon cycle, and social science perspectives on carbon. Since publication of SOCCR1, coordinated research from agencies in the three North American countries has enabled innovative observational, analytical, and modeling capabilities to further advance understanding of the North American carbon cycle (see Appendix D: Carbon Measurement Approaches and Accounting Frameworks, p. 834). Some of the report's main conclusions, based on the Key Findings of each chapter, are highlighted in Box ES.1, Main Findings of SOCCR2, p. 24.

What Is the Carbon Cycle, and Why Is It Important?

Carbon is the basis of life on Earth, forming bonds with oxygen, hydrogen, and nutrients to create the

[1] Soils and wetlands store both carbon and nitrogen in organic molecules that may be broken down to release CO_2, CH_4, and N_2O via various processes, many of which are linked and interdependent. In addition, the magnitude of these emissions depends on land-management practices and the biophysical environment, as well as the amount of (carbonaceous) organic matter in soils. In addition to CO_2 and CH_4 fluxes, N_2O exchanges between the biosphere and the atmosphere influence global carbon and nitrogen cycling.

Figure ES.1. Domain of the *Second State of the Carbon Cycle Report*. In addition to the land masses and inland waters of Canada, Mexico, and the United States (divided into U.S. National Climate Assessment regions), this report covers carbon dynamics in coastal waters, defined as tidal wetlands, estuaries, and the coastal ocean, the latter being defined by the Exclusive Economic Zone (EEZ). The seaward boundary of the EEZ is typically 200 nautical miles from the coast. The geographical scope of the U.S. analysis includes the conterminous United States, Alaska, Hawai'i, Puerto Rico, and the U.S. Virgin Islands. [Figure source: Christopher DeRolph, Oak Ridge National Laboratory.]

organic compounds that make up all living things. Essential for fundamental human activities and assets, carbon is a vital component of the fossil fuels used for energy production, cooking, agriculture, manufacturing, and transportation. The carbon cycle encompasses the physical, chemical, and biological processes that store or transfer carbon between different stocks or reservoirs (see Figure ES.2, p. 26). Examples of such reservoirs include the carbon stored as CO_2 and CH_4 gas in the atmosphere; as coal, petroleum, and natural gas (the primary energy sources for modern societies); and as organic and inorganic carbon in Earth's ocean, freshwaters, forests, grasslands, and soils. Carbon transfer among these reservoirs occurs via a range of different processes, such as plant uptake of atmospheric CO_2 for growth (photosynthesis), release of CO_2 to the atmosphere from organic matter decomposition and combustion, and "lateral" transfers of carbon and burial within aqueous systems (see Figure ES.3, p. 27, and Ch. 1: Overview of the Global Carbon Cycle, p. 42).

Box ES.1 Main Findings of SOCCR2

1. **Global Atmospheric Carbon Levels.** Globally, atmospheric carbon dioxide (CO_2) has risen over 40%, from a preindustrial level of about 280 parts per million (ppm) to the current concentration of more than 400 ppm. Over the same time period, atmospheric methane (CH_4) has increased from about 700 parts per billion (ppb) to more than 1,850 ppb, an increase of over 160%. Current understanding of atmospheric carbon sources and sinks confirms the overwhelming role of human activities, especially fossil fuel combustion, in driving these rapid atmospheric changes.

2. **Emissions from Fossil Fuel Combustion.** North American emissions from fossil fuel combustion have declined on average by 1% per year over the last decade, largely because of reduced reliance on coal, greater use of natural gas (a more efficient fossil fuel), and increased vehicle fuel efficiency standards. As a result, North America's share of global emissions decreased from 24% in 2004 to 17% in 2013. Continued growth in economic activity demonstrates that CO_2 emissions can be decoupled, at least partly, from economic activity. Projections suggest that by 2040, total North American absolute[2] fossil fuel carbon emissions could range from a 12.8% decrease to a 3% increase compared to 2015 levels (see Ch. 19: Future of the North American Carbon Cycle, p. 760).

3. **Atmospheric Carbon Removal by Land.** Evidence suggests that North American lands have persisted as a net carbon sink over the last decade, taking up about 600 to 700 teragrams of carbon (Tg C) per year, which is 11% to 13% of global carbon removal by terrestrial ecosystems (see Figure ES.2, p. 26; Ch. 2: The North American Carbon Budget, p. 71; and Ch. 8: Observations of Atmospheric Carbon Dioxide and Methane, p. 337). Previously conflicting atmospheric measurements and land inventories now converge on this range. Although uncertainties remain in estimates derived from both approaches, the weight of the evidence leaves little doubt about the direction and overall magnitude of the land sink. Future impacts from climate change, land-use change, and disturbances (both natural and human induced) may diminish this sink.

4. **Inland and Coastal Waters as Both Sources and Sinks.** Inland waters emit about 247 Tg C per year to the atmosphere but also bury about 155 Tg C per year in sediments. Tidal wetlands and estuaries represent a combined net sink of 17 Tg C per year from the atmosphere, and 14 Tg C per year are buried in sediments. The coastal ocean directly absorbs about 160 Tg C per year from the atmosphere and buries about 65 Tg C per year in sediments. These detailed findings and their uncertainties (see Figure ES.3, p. 27) represent marked improvements in the understanding of the carbon cycle in North America's aqueous environments and highlight the size of carbon transfers in water and across land-water interfaces. However, uncertainties for many of the fluxes remain large.

5. **Methane Concentration and Emissions.** Observations indicate that the globally averaged atmospheric CH_4 concentration increased at a rate of 3.8 ± 0.5 ppb per year from 2004 to 2013. Although this increase represents a significant rise in global emissions, the picture for North America is less clear. Most analyses of atmospheric data suggest relatively stable North American CH_4 emissions despite increases in natural gas extraction and use.

6. **Carbon Management Opportunities.** Analyses of social systems and their reliance on carbon demonstrate the relevance of carbon cycle changes to people's everyday lives and reveal feasible pathways to reduce greenhouse gas (GHG) emissions or increase carbon removals from the atmosphere. Such changes could include, for example, decreasing fossil fuel use (which has the largest reduction potential),

[2] "Absolute carbon emissions" refers to the total quantity of carbon being emitted rather than the total quantity in relation to some product or property. In contrast, carbon emissions intensity is the amount of carbon emitted per some unit of economic output, such as gross domestic product.

expanding renewable energy use, and reducing CH_4 emissions from livestock. Increased afforestation and improved agricultural practices also could remove emitted CO_2 from the atmosphere. Although activities in North America cannot alone reduce emissions enough to limit global temperature rise to 2°C, the estimated cumulative cost from 2015 to 2050 for the United States to reduce emissions by 80% relative to 2005 levels (an amount considered to be in line with the 2°C goal), by using a variety of technological options, is in the range of $1 trillion to $4 trillion (US$2005). The total annual cost in 2050 alone for climate change damages across health, infrastructure, electricity, water resource, agriculture, and ecosystems in the United States is conservatively estimated to range from $170 billion to $206 billion (US$2015; see Ch. 3: Energy Systems, p. 110).

7. **Carbon Accounting and Urban Environments.** Because urban environments in North America are the primary sources of anthropogenic carbon emissions, carbon monitoring and budgeting in these areas are extremely important. In addition to direct emissions, urban areas are responsible for indirect sources of carbon associated with goods and services produced outside city boundaries for consumption by urban dwellers. Careful accounting of direct and indirect emissions is necessary to avoid double counting of CO_2 fluxes measured in other sectors and to identify sources to inform management and policy. (For more details on alternatives for carbon accounting and emissions attribution, see Frameworks for Carbon Accounting, p. 15, in the Preface and Appendix D: Carbon Measurement Approaches and Accounting Frameworks, p. 834.)

8. **Projections of the Carbon Cycle.** Projections suggest that energy production, land-use change (especially urbanization), climatic changes such as warming and droughts, wildfires, and pest outbreaks will increase GHG emissions in the future. Carbon stored in soil pools in the circumpolar permafrost zone is at particular risk. With the current trajectory of global and Arctic warming, 5% to 15% of this carbon is vulnerable for release to the atmosphere by 2100.

9. **Ocean Acidification.** Rising CO_2 has decreased seawater pH at long-term observing stations around the world, including in the open ocean north of Oahu, Hawai'i; near Alaska's Aleutian Islands and the Gulf of Maine shore; and on Gray's Reef in the southeastern United States. This ocean acidification already has affected some marine species and altered fundamental ecosystem processes, with further effects likely.

10. **User-Inspired Science.** Demand for carbon cycle science from diverse institutions, including carbon registries, major corporations, municipal governments, utilities, and non-governmental organizations, has remained strong over the past decade. Social science research could map the capacity of these different organizations to use carbon cycle science to help identify relevant research questions and to produce information in formats that align with standard organizational practices and stakeholder needs.

11. **Research and Monitoring Gaps**. This report documents an improving ability to attribute observed changes in the North American carbon budget to specific causes. Additional research is needed to better understand the impacts of human activities on the carbon cycle, feedbacks between increasing CO_2 concentrations and terrestrial ecosystems, natural disturbance alterations caused by climate change, and societal responses to these changes. Understanding these processes and their interactions is essential for improving projections of future changes in the carbon cycle and addressing adaptation needs and management options. Advancing the understanding of carbon cycling and resource management on public, private, and tribal lands requires further research, as does improving the integration of social science with natural science related to the carbon cycle. Additional focused monitoring would benefit carbon accounting and management, particularly in Arctic and boreal regions, grasslands, wetlands, inland and coastal waters, and tropical ecosystems.

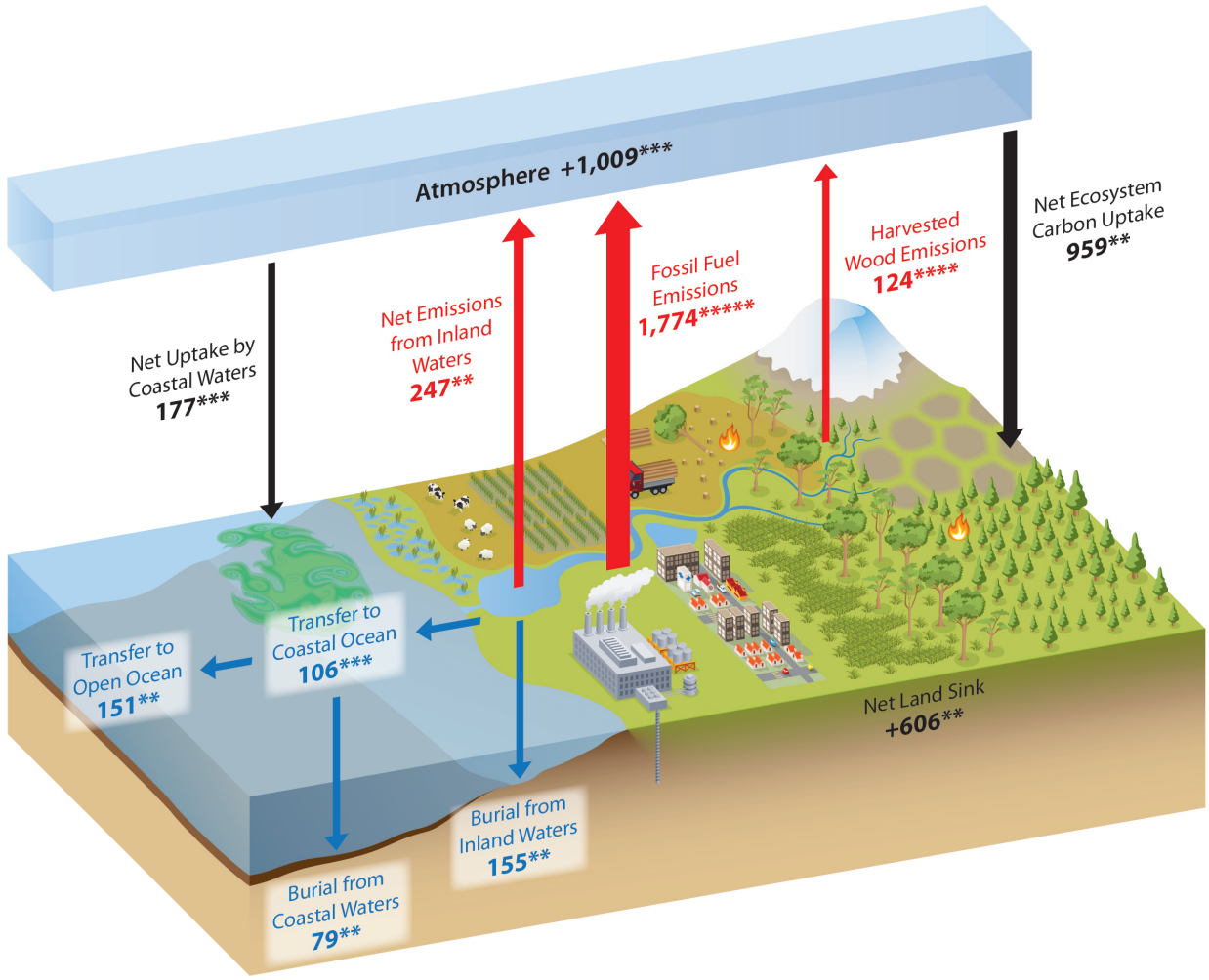

Figure ES.2. Major Carbon Fluxes of North America. Net fluxes and transfers of carbon among the atmosphere, land, and water are depicted in this simplified representation of the North American carbon cycle. The diagram includes fluxes of carbon dioxide but not methane or other carbon-containing greenhouse gases. These carbon flows include 1) emissions (red arrows); 2) uptake (black arrows); 3) lateral transfers (blue arrows); and 4) burial (blue arrows), which involves transfers of carbon from water to sediments and soils. Estimates—derived from Figure ES.3, p. 27, and Figure 2.3, p. 83, in Ch. 2: The North American Carbon Budget—are in teragrams of carbon (Tg C) per year. The increase in atmospheric carbon, denoted by a positive value, represents the net annual change resulting from the addition of carbon emissions minus net uptake of atmospheric carbon by ecosystems and coastal waters. The estimated increase in atmospheric carbon of +1,009 Tg C per year is from Figure 2.3, p. 83, and that value is slightly different from the +1,008 Tg C per year value used elsewhere in Ch. 2 because of mathematical rounding. Net ecosystem carbon uptake represents the balance of carbon fluxes between the atmosphere and land (i.e., soils, grasslands, forests, permafrost, and boreal and Arctic ecosystems). Coastal waters include tidal wetlands, estuaries, and the coastal ocean (see Figure ES.3 for details). The net land sink, denoted by a positive value, is the net uptake by ecosystems and tidal wetlands (Figure ES.3) minus emissions from harvested wood and inland waters and estuaries (Figure ES.3). For consistency, the land sink estimate of 606 Tg C per year is adopted from Ch. 2, p. 71. Because of rounding of the numbers in that chapter, this value differs slightly from the combined estimate from Figures ES.2 and ES.3 (605 Tg C per year). Asterisks indicate that there is 95% confidence that the actual value is within 10% (*****), 25% (****), 50% (***), 100% (**), or >100% (*) of the reported value. [Figure source: Adapted from Ciais et al., 2013, Figures 6.1 and 6.2; Copyright IPCC, used with permission.]

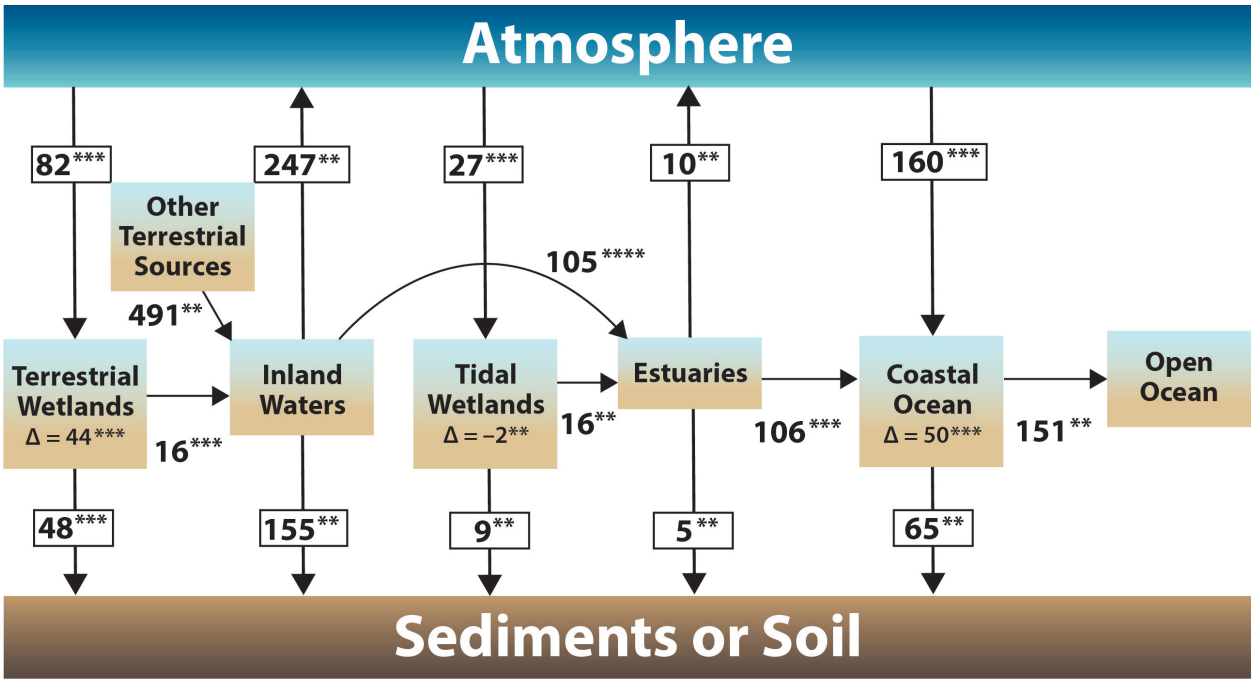

Figure ES.3. Total Carbon Budget of North American Aquatic Ecosystems. Flux estimates, in teragrams of carbon (Tg C) per year, are derived from Ch. 13: Terrestrial Wetlands, p. 507; Ch. 14: Inland Waters, p. 568; Ch. 15: Tidal Wetlands and Estuaries, p. 596; and Ch. 16: Coastal Ocean and Continental Shelves, p. 649. Carbon exchanges with the atmosphere are limited to carbon dioxide (CO_2) except for terrestrial wetlands, which include CO_2 and methane. Arrows leading from the atmosphere to different aquatic ecosystem compartments imply a loss of atmospheric carbon from the atmosphere to the ecosystem (a carbon sink). Arrows leading from the ecosystem to the atmosphere imply a loss of carbon from the ecosystem to the atmosphere (a carbon source). Horizontal arrows refer to transfer of carbon between ecosystems. Changes in some reservoir sizes are provided inside the boxes with deltas (Δ). Asterisks indicate that there is 95% confidence that the actual value is within 10% (*****), 25% (****), 50% (***), 100% (**), or >100% (*) of the reported value.

Carbon is also critical in regulating climate because carbon-containing GHGs[3] absorb radiant energy emitted from Earth's surface, thereby warming the planet. This warming creates a climate within the narrow range of conditions suitable for life. Changes in atmospheric concentrations of GHGs influence Earth's ecosystems and society in many ways, both positive and negative. Consequences of increasing GHGs include impacts on air quality, human health, water quality and availability, ecosystem productivity, species distributions, biological diversity, ocean chemistry, sea level rise, and many other processes that determine human well-being. Thus, the carbon cycle is tightly coupled to the environment, society, and the global climate system.

How Is the Global Carbon Cycle Changing?

The carbon cycle is changing at a much faster pace than observed at any time in geological history (see Ch. 17: Biogeochemical Effects of Rising Atmospheric Carbon Dioxide, p. 690). These changes primarily are attributed to current energy and transportation dependencies on the burning of fossil fuels, which releases previously stable or sequestered carbon. Also contributing to rapid changes in the carbon cycle are cement production and gas flaring, as well as net emissions from forestry, agriculture, and other land uses. The associated rise in atmospheric

[3] All GHGs absorb radiant energy, but two carbon-containing GHGs, CO_2 and CH_4, are responsible for a large fraction of this effect.

GHGs is largely responsible for Earth's increased temperature over the past 100 years. The global mean temperature in 2017 relative to the 1880 to 1920 average has increased by more than 1.25°C in response, as documented in the *Climate Science Special Report* (USGCRP 2017). Human-induced warming is having significant—usually negative—impacts including more frequent heatwaves, heavy precipitation, and coastal flooding, all of which lead to lost lives, damaged communities, and disrupted ecosystems.

Since SOCCR1, concentrations of atmospheric CO_2 and CH_4 have been on the rise (see Figure ES.4, this page). From 2007 to 2015, the global rate of increase averaged 2.0 ± 0.1 parts per million (ppm) per year for CO_2 and 3.8 ± 0.5 parts per billion (ppb) per year for CH_4 (see Ch. 8: Observations of Atmospheric Carbon Dioxide and Methane, p. 337). Current understanding of the sources and sinks of atmospheric carbon confirms the overwhelming role of human activities, especially fossil fuel combustion, in driving the atmospheric changes in CO_2 concentrations (see Ch. 1: Overview of the Global Carbon Cycle, p. 42). In North America, projections suggest that by 2040, total fossil fuel emissions, in terms of total carbon, will range from 1.5 petagrams of carbon (Pg C) to 1.8 Pg C per year, with the United States contributing 80% of this total. Compared to 2015 levels, these projections represent a range from a 12.8% decrease to a 3% increase in absolute emissions of carbon (see Ch. 19: Future of the North American Carbon Cycle, p. 760).

Globally, land and ocean ecosystems are net sinks of atmospheric carbon, taking up more carbon annually than they release. The most recent estimates suggest that from 2006 to 2015, land ecosystems removed about 3.1 ± 0.9 Pg C per year while the ocean removed 2.3 ± 0.5 Pg C per year. Combined, these removals equal about half the amount of CO_2 emitted from fossil fuel combustion and land-use change (see Ch. 1: Overview of the Global Carbon Cycle, p. 42). However, a range of research suggests the carbon uptake capacity of all these systems may decline in the future, with some reservoirs switching from a net sink to a net source of carbon to the atmosphere.

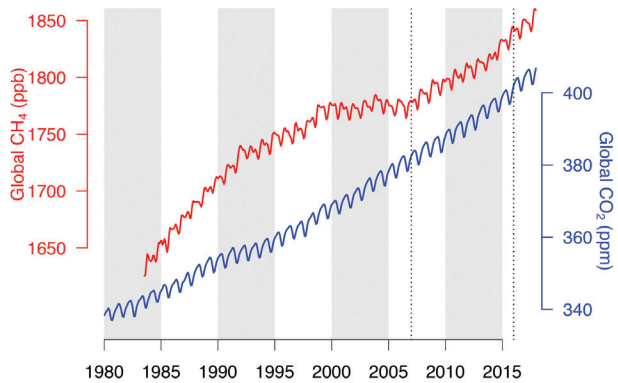

Figure ES.4. Global Monthly Mean Atmospheric Methane (CH_4) and Carbon Dioxide (CO_2) Concentrations. CH_4 values (red) and CO_2 values (blue) are averaged from the background surface sites of the National Oceanic and Atmospheric Administration's global monitoring network. Dotted vertical lines in 2007 and 2016 represent approximate reference times for publication of the *First State of the Carbon Cycle Report* (CCSP 2007) and development of the *Second State of the Carbon Cycle Report*. Concentrations of CH_4 in parts per billion (ppb), CO_2 in parts per million (ppm). [Simplified from Figure 8.1 in Ch. 8: Observations of Atmospheric Carbon Dioxide and Methane, p. 339.]

Carbon Sources, Sinks, and Stocks in North America

In North America, GHGs are emitted primarily from fossil fuel burning; cement production; organic matter decomposition in inland lakes and rivers; land-use changes; and agricultural activities, particularly on drained peatland soils. Conversion of carbon gases (mainly CO_2) to organic matter through photosynthesis occurs in forests, grasslands, other land ecosystems, and coastal waters. Just under one-half of CO_2 emissions (43%) are offset by carbon sinks in the land and coastal waters. Compared to SOCCR1, this report defines more land and aquatic ecosystem components, providing an improved understanding of their respective roles in carbon cycling. Selected highlights about the North American carbon cycle follow.

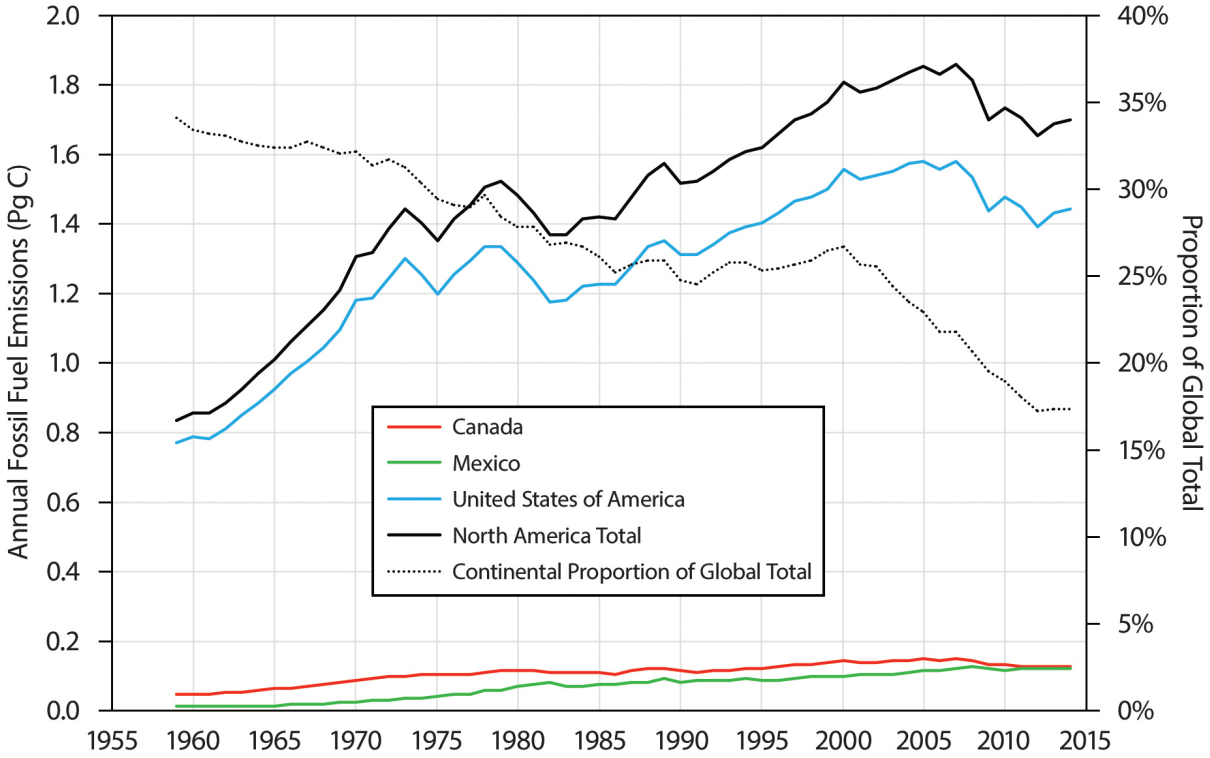

Figure ES.5. Annual North American Fossil Fuel Emissions from 1959 to 2014. Values are given in petagrams of carbon (Pg C) for each country and for the continent as a whole (solid lines, left vertical axis). The dotted line shows the North American proportion of total global emissions (right vertical axis). [From Figure 2.2, p. 81, in Ch. 2: The North American Carbon Budget. Data source: Carbon Dioxide Information Analysis Center (Boden et al., 2017).]

Fossil Fuels Are Still the Largest Source

Carbon dioxide emissions from fossil fuels in North America averaged 1,774 teragrams of carbon (Tg C) per year (±6%) from 2004 to 2013 (see Figure ES.2, p. 26). This estimate is similar to the 1,856 Tg C per year (±10%) reported for the decade prior to 2003 (CCSP 2007). From 2004 to 2013, CO_2 fossil fuel emissions decreased about 1% per year because of various market, technology, and policy drivers, as well as the financial crisis (see Ch. 3: Energy Systems, p. 110). During this same time period, North America likely acted as a net source of CH_4 to the atmosphere, contributing on average about 66 Tg CH_4 per year. Currently, the United States is responsible for about 85% of total fossil fuel emissions from North America. As of 2013, the continent contributes about 17% of total global emissions from fossil fuels, a decline from about 24% in 2004 because of increasing emissions elsewhere and reduced emissions in the United States (see Figure ES.5, this page; Ch. 2: The North American Carbon Budget, p. 71; Ch. 3: Energy Systems, p. 110; and Ch. 8: Observations of Atmospheric Carbon Dioxide and Methane, p. 337).

Aquatic Ecosystems Are Both Sources and Sinks

Although SOCCR1 did not directly quantify net CO_2 emissions from inland waters to the atmosphere, this report estimates those emissions at about 247 Tg C per year (±100%; see Figure ES.2, p. 26; Figure ES.3, p. 27; and Ch. 14: Inland Waters, p. 568). Burial in lakes and reservoirs, which is part of the terrestrial carbon sink, is about 155 Tg C per year (±100%), a level much higher than a similar

estimate made for SOCCR1 (25 Tg C per year ± 120%) but still within the uncertainty bounds of each estimate, making the identification of a trend impossible (see Figure ES.3 and Ch. 14). Lateral transfers from inland waters to estuaries total about 105 Tg C per year and from estuaries to the coastal ocean about 106 Tg C per year (±30%; see Ch. 14 and Ch. 15: Tidal Wetlands and Estuaries, p. 596). The transfer from the coastal ocean to the open ocean is estimated to be 151 Tg C per year (±70%; see Ch. 16: Coastal Ocean and Continental Shelves, p. 649). These estimates were not included in SOCCR1, except for transfers from rivers to coastal waters, which were estimated at 35 Tg C per year (±100%).

Carbon losses from inland waters in North America total about 507 Tg C per year (see Figure ES.3, p. 27). Although there is a reasonably good basis for this estimate, knowledge of carbon sources to inland waters is extremely poor. The only source that has been estimated is the lateral transport of dissolved organic carbon from terrestrial wetlands, which equals only 16 Tg C per year. Other sources include different types of carbon from terrestrial wetlands (e.g., dissolved inorganic carbon and particulate carbon) and carbon from surface runoff, groundwater flow, and erosion. Assuming no accumulation of carbon in inland waters, these sources should total 491 Tg C per year (see Figure ES.3, p. 27).

Three types of wetlands constitute small net sinks of CO_2: 1) terrestrial nonforested wetlands, estimated at 60 Tg C per year; 2) forested wetlands, estimated at 67 Tg C per year (also included in the forestland category); and 3) tidal wetlands, estimated at 27 Tg C per year (see Figure ES.3; Ch. 13: Terrestrial Wetlands, p. 507; and Ch. 15, p. 596). Terrestrial wetlands are a natural source of CH_4 (see Ch. 13), annually emitting an estimated 45 Tg of carbon as CH_4 (±75%). Carbon moving in and out of terrestrial wetlands cannot be fully traced. The carbon budget (see Figure ES.3) does not balance because the net uptake from the atmosphere (82 Tg C per year equals CO_2 uptake minus CH_4 release) exceeds by 26 Tg C per year the sum of accumulation in vegetation (44 Tg C per year) and soils (48 Tg C per year) and the loss of dissolved organic carbon (16 Tg per year; see Figure ES.3).

Land and Coastal Waters Are a Net Sink

Natural sinks on North American land and adjacent coastal waters offset approximately 43% of the total fossil fuel emissions of CO_2 from 2004 to 2013 (see Ch. 2: The North American Carbon Budget, p. 71). The magnitude of the North American terrestrial sink estimated from "bottom-up" methods (i.e., inventory and biosphere-based approaches such as field measurements and ecosystem process models) is about 606 Tg C per year (±50%). This value is derived from estimates of net uptake by ecosystems and tidal wetlands minus emissions from harvested wood, inland waters, and estuaries (see Figure ES.2, p. 26). The bottom-up estimate is about the same as the estimated 699 Tg C per year (±12%) inferred by "top-down" (atmospheric-based) observations but with larger uncertainties (see Ch. 2, p. 71, and Ch. 8: Observations of Atmospheric Carbon Dioxide and Methane, p. 337).

The coastal ocean of North America (the Exclusive Economic Zone, not including tidal wetlands and estuaries) is an estimated sink of 160 Tg C (±50%) annually, based on estimates of air-sea carbon fluxes and a numerical model (see Figure ES.3). This net uptake from the atmosphere is driven primarily by fluxes in high-latitude regions (see Ch. 16: Coastal Ocean and Continental Shelves, p. 649).

Soil Stocks

Carbon stocks in North American soils are estimated as 627 Pg C, representing more than 90% of the continent's total carbon stocks including biomass (see Table 2.1, p. 79, in Ch. 2: The North American Carbon Budget). Because soil carbon concentrations vary by depth, estimates of soil carbon depend on the soil depth considered in surveys, which often do not account for deeper soil carbon. Summing the estimates of organic carbon contained in soils to a depth of 1 m from Canada, the United States, and Mexico yields about 400 Pg C (see Ch. 12: Soils, p. 469). Globally, stocks in the

circumpolar Arctic and boreal regions are estimated as 1,400 to 1,600 Pg C based on inventories of soils and sediments to a 3-m or more depth. About one-third of this carbon is in North America (see Ch. 11: Arctic and Boreal Carbon, p. 428).

Forests

Forests, including their soils, constitute the largest component of the land sink, taking up a net 217 Tg C per year (±25%) from 2004 to 2013 (see Ch. 9: Forests, p. 365). Across the continent, afforestation added 27 Tg C per year and deforestation led to a loss of 38 Tg C per year (see Ch. 9). Woody encroachment, which refers to increasing density of woody vegetation on grasslands and shrublands, is part of the carbon sink, and it is included within the terrestrial categories of forests and grasslands as appropriate.

Agriculture

Agricultural GHG emissions totaled 567 Tg CO_2 equivalent (CO_2e)[4] for the United States in 2015, 60 Tg CO_2e for Canada in 2015, and 80 Tg CO_2e for Mexico in 2014. These estimates do not include emissions from land-use change involving agriculture, as reported in each country's GHG inventory submission to the United Nations Framework Convention on Climate Change. The major non-CO_2 emissions from agricultural sources are N_2O from cropped and grazed soils and manure and enteric CH_4 emissions from livestock production (see Ch. 5: Agriculture, p. 229). Because management plays a large role in determining the carbon cycle of agricultural systems, there are significant opportunities to reduce emissions and increase the magnitude of carbon sinks in these areas.

Arctic and Boreal Ecosystems

Arctic and boreal ecosystems are estimated to be a small sink of 14 Tg C annually (see Ch. 2: The North American Carbon Budget, p. 71, and Ch. 11: Arctic and Boreal Carbon, p. 428). Confidence in this estimate is low because the extent to which these results overlap or leave gaps with other terrestrial categories, particularly boreal forests and terrestrial wetlands, is not clear due to the relatively limited data coverage for these northern ecosystems.

Effects of Carbon Cycle Changes on North Americans and Their Environments

Changes to the carbon cycle can affect North Americans in a wide variety of ways. For example, the ocean provides multiple benefits or "services," including the provision of fish, carbon storage, coastal protection by reefs, and climate modulation. These services face significant risks from the combined effects of ocean acidification, warming ocean waters, and sea level rise (see Ch. 17: Biogeochemical Effects of Rising Atmospheric Carbon Dioxide, p. 690). Rising atmospheric CO_2 has decreased seawater pH, leading to ocean acidification as evidenced from measurements at long-term observing stations around North America (see Ch. 16: Coastal Ocean and Continental Shelves, p. 649, and Ch. 17). This decrease in pH, mainly due to oceanic uptake of CO_2, also is affected by other factors including circulation and eutrophication (i.e., nutrient enrichment of water that can lead to increased primary production and, subsequently, poorer water quality). Ocean acidification also enhances corrosive conditions and can inhibit the formation of calcium carbonate shells essential to marine life. Compared to many other coastal waters, Arctic and North Pacific coastal waters are already more acidic, and therefore small changes in pH due to CO_2 uptake have affected marine life in these waters more significantly (see Ch. 16). In addition to impacts on marine species, ocean acidification has altered fundamental ecosystem processes, with further effects likely in the future.

In terrestrial ecosystems, rising atmospheric CO_2 enhances photosynthesis and growth and increases water-use efficiency (see Ch. 17: Biogeochemical

[4] Amount of CO_2 that would produce the same effect on the radiative balance of Earth's climate system as another greenhouse gas, such as CH_4 or N_2O, on a 100-year timescale. For comparison to units of carbon, each kg CO_2e is equivalent to 0.273 kg C (0.273 = 1/3.67). See Box P.2, p. 12, in the Preface for details.

Effects of Rising Atmospheric Carbon Dioxide, p. 690). These carbon cycle–induced increases in plant growth and efficiency are referred to as "CO_2 fertilization." For example, crops exposed to higher atmospheric CO_2 often show increased yield. However, the CO_2 fertilization effect is not observed consistently in all ecosystems because of nutrient limitations or other factors. Furthermore, CO_2 fertilization typically is associated with increased leaf fall and root production, which can enhance microbial decomposition of organic materials in soils, thereby increasing net CO_2 emissions to the atmosphere (see Ch. 12: Soils, p. 469). All these changes have altered and will continue to alter vegetation composition (e.g., species distribution, biodiversity, and invasive species), carbon distribution and storage, terrestrial hydrology, and other ecosystem properties. Current and future changes to climate that are driven by altered carbon cycling also will affect ecosystems and their services, as well as interact with effects such as ocean acidification and CO_2 fertilization.

Overall, alterations to the North American carbon cycle will continue to affect the benefits that terrestrial and ocean systems provide to humans. The effects of rising atmospheric CO_2 concentrations interact with climate, sea level rise, and other global changes as described in SOCCR2 companion reports such as the *Third National Climate Assessment* (Melillo et al., 2014) and *Climate Science Special Report* (USGCRP 2017). For example, the frequency and intensity of disturbances such as fire, insect and pathogen outbreaks, storms, and heatwaves are expected to increase with higher temperatures and climate variability. Moreover, ecosystem responses to and interactions with such effects are often unpredictable and depend on ecosystem type, disturbance frequency, and magnitude of events (see Ch. 17, p. 690).

A Systems Approach to Linking the Carbon Cycle and Society

Carbon is a key element in multiple social, ecological, physical, and infrastructural realms including croplands, grasslands, forests, industry, transportation, buildings, and other structures (see Ch. 3–10, beginning on p. 110). As described in this report, North American social and economic activities, practices, and infrastructures significantly affect the carbon cycle. Energy use predominantly involves burning carbon-based fuels (see Ch. 3: Energy Systems, p. 110), but society also uses carbon in other less obvious ways such as food and buildings. Carbon is thus embedded in social life (see Ch. 6: Social Science Perspectives on Carbon, p. 264), and widespread variations in everyday activities result in carbon emissions that cause ripples of intended and unintended social and biophysical effects.

Not only are all parts of the carbon cycle tightly interlinked, they also interact with climate and society in complex ways that are not fully understood (see Figure ES.6, p. 33, and Ch. 18: Carbon Cycle Science in Support of Decision Making, p. 728). Given this complexity, a systems approach can provide valuable assistance in identifying mechanisms to reduce carbon emissions to the atmosphere. Such an approach examines carbon comprehensively, holistically, and from an interdisciplinary viewpoint and considers social, economic, and environmental factors as highlighted in examples that follow.

Energy Systems

System drivers and interactions within the energy sector are particularly complex. Differences in social practices, technical and infrastructural efficiency, market dynamics, policies, waste management, and environmental conditions explain variations in observed levels of energy use and land use, which are two key drivers of carbon emissions across North American households, organizations, firms, and socioecological systems (see Figure ES.6, p. 33, and Ch. 18, p. 728). Carbon emissions from burning fossil fuels have decreased because of growth in renewables, new technologies (such as alternative fuel vehicles), rapid increases in natural gas production, the 2007 to 2008 global financial crisis, and more efficient energy production and use (see Figure ES.5, p. 29; Ch. 2: The North American Carbon Budget, p. 71; and Ch. 3: Energy Systems, p. 110). Social mechanisms have influenced carbon emissions through acceptance of rooftop solar energy

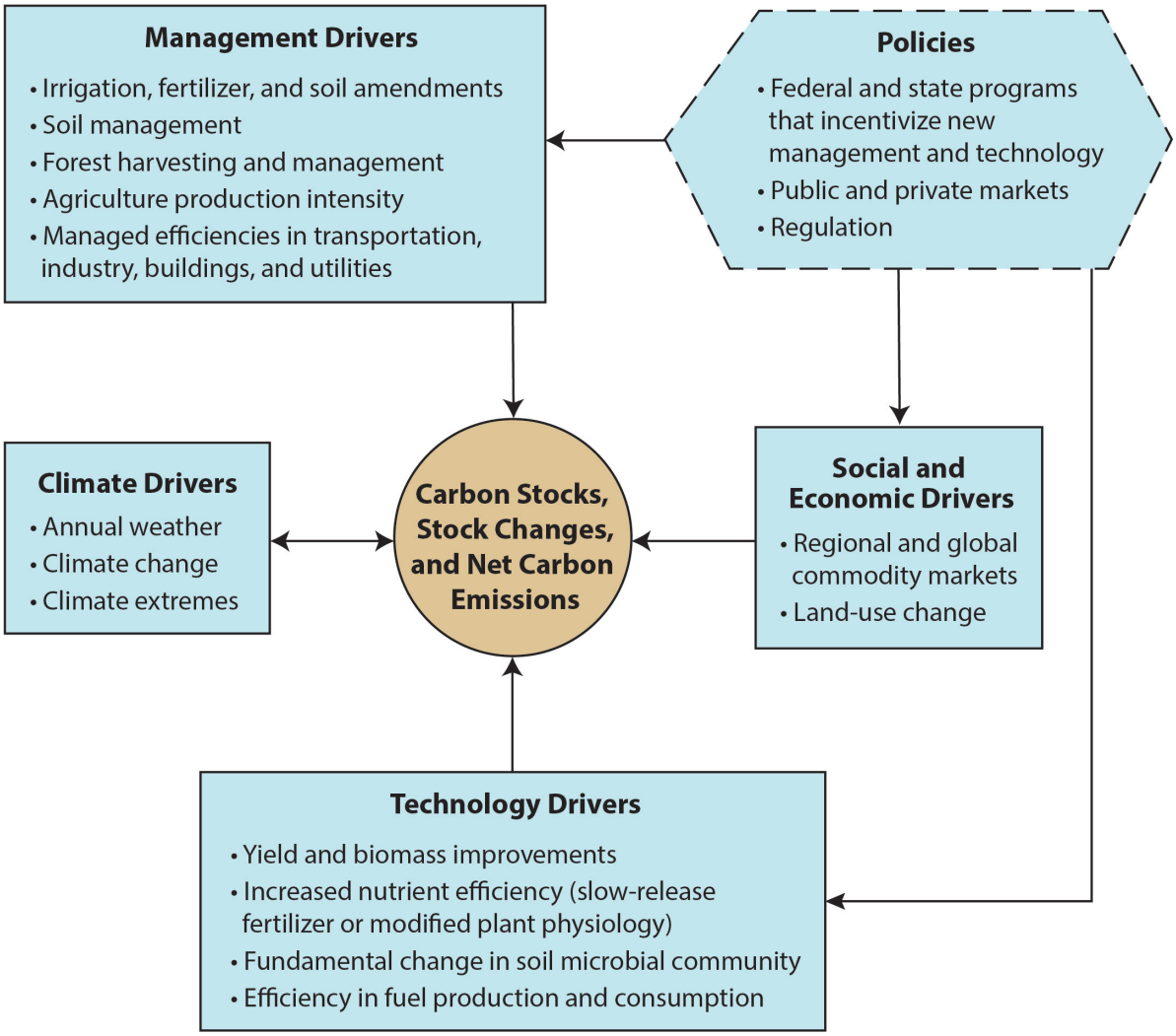

Figure ES.6. Primary Drivers of Carbon Stocks and Emissions in Select Sectors. Efforts to understand and estimate future carbon stocks and emissions require considering and representing the factors that drive their change. This schematic illustrates examples of components needed to represent carbon stock changes prior to addressing policy drivers. [From Figure 18.1, p. 730, in Ch. 18: Carbon Cycle Science in Support of Decision Making.]

and wind farms, the dynamics of routines in provision (i.e., attempts by suppliers to encourage and increase demand through marketing), and demand patterns related to the locus of work and the cultural definition of approved practices (see Ch. 6: Social Science Perspectives on Carbon, p. 264). Although social drivers can lock in dependencies for particular energy systems, North American energy systems are poised for significant infrastructure investment, given the age and condition of transportation infrastructure and existing components for energy generation, transmission, and storage (see Ch. 3: Energy Systems, p. 110).

Urban Areas

Urban areas occupy only 1% to 5% of the North American land surface but are important sources

of both direct anthropogenic carbon emissions and spatially concentrated indirect emissions embedded in goods and services produced outside city boundaries for consumption by urban users (see Ch. 4: Understanding Urban Carbon Fluxes, p. 189). The built environment (i.e., large infrastructural systems such as buildings, roads, and factories) and the regulations and policies shaping urban form, structure, and technology (such as land-use decisions and modes of transportation) are particularly important in determining urban carbon emissions. Such societal drivers can lock in dependence on fossil fuels in the absence of major technological, institutional, and behavioral change. Moreover, some fossil fuel–burning infrastructures can have lifetimes of up to 50 years. Urban areas also are important sites for policy- and decision-making activities that affect carbon fluxes and emissions mitigation. Co-benefits of urban mitigation efforts can be considerable, particularly in terms of improvements in air quality and human health, as well as reductions in the heat island effect (i.e., elevated ambient air temperatures in urban areas).

Agricultural Practices

Factors driving GHG emissions from agricultural activities include the creation of new croplands from forests or grasslands, nitrogen fertilizer use, and decisions about tillage practices and livestock management. Trends in global commodity markets, consumer demands, and diet choices also have large impacts on carbon emissions through land-use and land-management changes, livestock systems, inputs, and the amount of food wasted (see Ch. 5: Agriculture, p. 229). Policy incentives and local regulations affect some of these decisions.

Tribal Lands

Carbon cycling and societal interactions on tribal lands have important similarities to and differences from those on surrounding public or private lands. Managing tribal lands and resources poses unique challenges to Indigenous communities because of government land tenure, agricultural and water policies, relocation of communities to reservations in remote areas, high levels of poverty, and poor nutrition. Nevertheless, multiple tribal efforts involve understanding and benefitting from the carbon cycle. For example, there are several case studies examining traditional practices of farming and land management for sequestering carbon on tribal lands (see Ch. 7: Tribal Lands, p. 303).

Land-Use Change

Land-use change has long been a driver of net reductions in atmospheric CO_2 emissions in the United States and Canada. Over the past decade, Canada and Mexico have lost carbon from land-use changes involving forests, but in the United States carbon losses from deforestation have balanced carbon gains from new forestland. Recent increases in natural disturbance rates, likely influenced by climate change and land-management practices, have diminished the strength of net forest uptake across much of North America. In addition, carbon emissions from the removal, processing, and use of harvested forest products offset about half of the net carbon sink in North American forests (see Ch. 9: Forests, p. 365).

Projections of the Future Carbon Cycle, Potential Impacts, and Uncertainties

Future changes to the carbon cycle are projected using different kinds of models based on past trends, current data and knowledge, and assumptions about future conditions. Model projections reported in SOCCR2 seek to understand the potential of different components of North American ecosystems to serve as carbon sources or sinks, even though such projections have uncertainties (see Box ES.2, Projection Uncertainties, p. 35).

The best available projections suggest that emissions from fossil fuel combustion in the energy sector will continue into the future. These projections also indicate that by 2040, total North American fossil fuel emissions could range from 1.5 to 1.8 Pg C per year, a range representing a 12.8% decrease to 3% increase in emissions compared to 2015 levels (see Ch. 19: Future of the North American Carbon Cycle, p. 760). Projections include the combined effects of policies, technologies, prices, economic

Box ES.2 Projection Uncertainties

Predicting the future carbon cycle is challenging for many reasons. One challenge is land-use change, a major contributor to the North American carbon sink. Future land use and land-use change are hard to predict, inhibiting projections of the land's capacity to continue serving as a carbon sink. Likewise, the future trajectory of fossil fuel emissions may shift because of unexpected technology changes or economic trends that introduce uncertainty into the projections. For example, the recent increase in hydraulic fracturing shifted new power plant sources away from coal and toward natural gas, a change that decreased carbon dioxide (CO_2) emissions because natural gas is a more efficient, cleaner-burning fuel (see Ch. 1: Overview of the Global Carbon Cycle, p. 42, and Ch. 3: Energy Systems, p. 110). Significant carbon cycling effects also may arise from unpredictable economic conditions, such as the 2007 to 2008 global economic recession, which reduced fossil fuel use considerably. There are also uncertainties in the scientific understanding of terrestrial and oceanic ecosystems. For example, increasing atmospheric CO_2 enhances plant growth, but other factors such as temperature, moisture, and nutrient availability constrain plant growth; it is the balance and interactions of these controls that will determine the overall effect. Models offer powerful tools for considering future scenarios, and, in this context, atmospheric carbon predictions can be used to guide policymaking, taking into consideration the levels of uncertainty of particular forecasts of future conditions (see Ch. 19: Future of the North American Carbon Cycle, p. 760).

growth, demand, and other variables. Human activities, including energy and land management, will continue to be key drivers of carbon cycle changes into the future. A wide range of plausible futures exists for the North American energy system in regard to carbon emissions. For the United States, backcasting scenarios suggest that a significant reduction in emissions is plausible.

The persistence of the overall North American land carbon sink is highly uncertain, with models projecting that terrestrial ecosystems could continue as net sinks of carbon (up to 1.5 Pg C per year) or switch to net sources of carbon to the atmosphere (up to 0.6 Pg C per year) by the end of the century. Low confidence in these projections results from uncertainties about the complex interactions among several factors, ranging from emissions scenarios, climate change, rising atmospheric CO_2, and human-driven changes to land cover and land use (see Ch. 19, p. 760).

Soils store a majority of land carbon, particularly the permafrost soils of northern high-latitude regions, which are experiencing the most rapid rates of warming caused by climate change. Increased temperatures very likely will lead to accelerated rates of permafrost thaw, releasing previously frozen soil carbon to the atmosphere. Globally, rising temperatures could cause the soil pool of 1,500 to 2,400 Pg C to release 55 ± 50 Pg C by 2050. However, the magnitude and timing of these carbon losses are not well understood, partly because of poor coverage and distribution of measurements, as well as inadequate model representation of permafrost feedbacks (see Ch. 11: Arctic and Boreal Carbon, p. 428; Ch. 12: Soils, p. 469; and Ch. 19: Future of the North American Carbon Cycle, p. 760).

The Exclusive Economic Zone of North American coastal areas has taken up 2.6 to 3.4 Pg C since 1870 and is projected to take up another 10 to 12 Pg C by 2050 under business-as-usual, human-driven emissions scenarios. However, coastal ecosystems such as

mangroves, wetlands, and seagrass beds that historically have removed carbon from the atmosphere are particularly vulnerable to loss of stored carbon caused by the combination of sea level rise, warming, storms, and human activity; the extent and impact of these vulnerabilities are highly uncertain (see Ch. 19, p. 760). Taken together, these projections portray significant but uncertain future potential changes in the carbon cycle and associated consequences.

Carbon Management and Mitigation

The anthropogenic effects on the carbon cycle as synthesized in this report clearly show there is ample capacity to affect carbon pools and cycles. In the past, such effects have mostly been unintentional, but they underscore contemporary policy and management opportunities for managing the North American carbon cycle and mitigating carbon emissions. There is global scientific consensus for the need to limit carbon emissions and resultant projected global warming in this century to less than 2°C above preindustrial levels (and preferably to less than 1.5°C) while also reducing net anthropogenic GHG emissions to zero via "negative emissions" technologies, carbon management, and mitigation. Based on current rates of global fossil fuel use and land-use change, emissions could be sufficient in about 20 years to cause global temperature to increase 2°C, assuming the land and ocean sinks remain at current levels (see Ch. 1: Overview of the Global Carbon Cycle, p. 42). According to global climate simulations, cumulative carbon emissions since preindustrial times cannot exceed about 800 Pg C for a 67% chance that the global average temperature increase would be less than 2°C. As of 2015, total cumulative emissions were about 570 Pg C. Therefore, to keep warming below 2°C, probably no more than an additional 230 Pg C may be released globally.[5] National, international, and local initiatives provide mechanisms for Mexico, Canada, and the United States to decrease carbon emissions (see Box ES.3, Multiscale Efforts to Reduce Carbon Emissions, p. 37). To help reduce emissions, subnational entities in North America have implemented activities such as green building codes and efforts related to regional energy systems (see Ch. 3: Energy Systems, p. 110).

Carbon Management Tools and Options

There are multiple options to decrease GHG emissions or increase carbon sinks. One is to reduce the use of fossil fuels, replacing them with renewable energy sources (e.g., solar, wind, biofuels, and water) that often release less carbon into the atmosphere. Other strategies involve capturing CO_2 at point sources, compressing and transporting it (usually in pipelines), and safely and securely storing it deep underground. Negative emissions activities represent a third option that leverages approaches to remove previously emitted CO_2 by increasing its capture from the atmosphere and its subsequent long-term storage, mainly in terrestrial, geological, and oceanic reservoirs (see Ch. 1: Overview of the Global Carbon Cycle, p. 42). Each option has benefits but also tradeoffs that are important to evaluate.

Multiple lines of evidence throughout SOCCR2 demonstrate that humans have the capacity to significantly affect the carbon cycle. Understanding the mechanisms and consequences of these effects offers opportunities to use knowledge of the carbon cycle to make informed and potentially innovative carbon management and policy decisions. In the past, planners have assumed economically rational energy use and consumption behaviors and thus were unable to predict actual choices, behaviors, and intervening developments, leading to large gaps between predicted versus actual purchase rates of economically attractive technologies with lower carbon footprints (see Ch. 6: Social Science Perspectives on Carbon, p. 264). Approaches that are people-centered and multidisciplinary emphasize that carbon-relevant decisions often are not about energy, transportation, infrastructure, or agriculture, but rather style, daily living, comfort, convenience, health, and other priorities (see Ch. 6). With this

[5] These values are for CO_2 emissions. Ch. 1: Overview of the Global Carbon Cycle, p. 42, further explains and expands on these estimates and includes consideration of the non-CO_2 greenhouse gases, CH_4 and N_2O.

Box ES.3 Multiscale Efforts to Reduce Carbon Emissions

Many countries announced voluntary, nonbinding greenhouse gas (GHG) emissions reduction targets and related actions in the lead-up to the 2015 Conference of the Parties to the United Nations Framework Convention on Climate Change in Paris. These announcements addressed emissions through 2025 or 2030 and took a range of forms (UNFCCC 2015). At the state to local level, many U.S. and Mexican states and Canadian provinces have climate action plans, and a few have aggressively acted to reduce carbon emissions (see Ch. 3: Energy Systems, p. 110, and Ch. 4: Understanding Urban Carbon Fluxes, p. 189). Most notable are the "cap-and-trade" program established in California in 2012 (CARB 2018) and the Climate Mitigation Policies developed by Mexican states such as Chiapas. Recently, many U.S. states, led by their governors, have made state-level commitments to reduce GHG emissions. In addition, thousands of North American cities have made pledges or joined municipal networks to develop policies and programs, including benchmarking initiatives, designed to track and reduce carbon dioxide emissions. Research has shown that cities often are motivated by potential co-benefits of mitigation measures, such as cost savings and improved air quality, but that implementing such measures likely will present cities with political, organizational, and financial obstacles.

consideration, some technical and science-based tools and carbon management options are highlighted here. These options aim to reduce the likelihood of rapid climate change in the future and increase the benefits of a well-managed carbon cycle (see Ch. 3: Energy Systems, p. 110; Ch. 6, p. 264; and Ch. 18: Carbon Cycle Science in Support of Decision Making, p. 728).

Energy Sector. Mitigation options include reduced use of carbon-intensive energy sources, such as oil and coal, and increased use of natural gas and renewables. Replacement of aging infrastructure with modern and more efficient facilities can also reduce emissions. Equally important are market mechanisms and technological improvements that increase energy-use efficiency and renewable energy production from wind, solar, biofuel, and geothermal technologies (see Ch. 3: Energy Systems, p. 110).

Urban Areas. Emissions reductions in these areas mostly focus on transportation, buildings, and energy systems. Transportation options include facilitating the transition to lower-emission vehicles and expanding the availability and use of public transit. Green building design and the energy embodied in building construction are metrics incorporated into green building codes (see Ch. 4: Understanding Urban Carbon Fluxes, p. 189). Replacing aging pipelines can also reduce leakage of natural gas.

Carbon Capture and Storage. Capturing carbon released from the burning of fossil fuels directly prevents CO_2 from entering the atmosphere. However, the technology remains costly and would benefit from additional research (see Ch. 3, p. 110).

Land-Use and Land-Management Changes. Carbon management options include 1) avoiding deforestation; 2) sequestering carbon (i.e., accumulating and storing it long term) through afforestation, agroforestry, or grassland restoration; 3) improving forest management to increase and maintain higher levels of carbon stocks or to increase CO_2 uptake from the atmosphere; and 4) directing harvest removals toward either biomass energy as a substitute for fossil fuels or long-lived wood products as substitutes for more fossil fuel–intensive building materials. Conversion of grasslands to croplands,

however, is likely to reduce carbon stocks (see Ch. 5: Agriculture, p. 229; Ch. 9: Forests, p. 365; Ch. 10: Grasslands, p. 399; and Ch. 12: Soils, p. 469). Accumulating carbon into vegetation and soils could remove 1.6 to 4.4 Pg C per year globally from the atmosphere, but the availability of land area, nutrients, and water could constrain such efforts (see Ch. 12).

Grazing and Livestock Management. These management activities affect grassland carbon stocks and their net carbon uptake by tens of teragrams per year (see Ch. 10, p. 399). Although various management strategies can reduce CH_4 emissions from ruminants (i.e., enteric) by 20% to 30% and from manure by 30% to 80%, they need to be evaluated over appropriate scales to account for emissions co-effects, such as improved land productivity (see Ch. 5, p. 229).

Agriculture Cropland and Waste Management. Mitigation strategies include covering the land year-round with deeply rooted crops, perennials, or cover crops; protecting the carbon in agricultural soils via residue management and improved nutrient management; and reducing food waste and inefficiencies. In addition, optimizing nitrogen fertilizer to sustain crop yield and reduce nitrogen losses to air and water reduces GHG emissions, protects water and air quality, decreases CH_4 fluxes in flooded or relatively anoxic systems, and provides food for a growing population (see Ch. 5, p. 229, and Ch. 12, p. 469).

Wetland Restoration or Creation. These efforts will affect wetland CO_2 and CH_4 fluxes, which vary widely among wetland sites, type, and time since restoration (see Ch. 13: Terrestrial Wetlands, p. 507, and Ch. 15 Tidal Wetlands and Estuaries, p. 596). In the long term, restored wetlands are considered carbon sinks because of plant uptake and subsequent organic matter accumulation.

Tribal Lands. Indigenous communities in the United States, Canada, and Mexico are applying traditional knowledge through sustainable management of forests, agriculture, and natural resources on tribal lands. Emerging carbon trading markets provide opportunities for these communities to benefit economically from such initiatives (see Ch. 7: Tribal Lands, p. 303). Successful efforts on tribal lands provide examples that could be followed on non-tribal lands.

Costs, Co-Benefits, and Tradeoffs

Estimates suggest that the cumulative cost over 35 years of reducing GHG emissions to meet a 2°C trajectory by 2050 ranges from $1 trillion to $4 trillion (US$2005) in the United States. Alternatively, the annual cost of not reducing emissions is conservatively estimated at $170 billion to $206 billion (US$2015) in the United States in 2050 (see Ch. 3: Energy Systems, p. 110).

Strategies for reducing carbon emissions often result in co-benefits such as improvements in air quality and energy-use efficiency, increased revenues, economic savings to taxpayers, greater crop productivity, and enhanced quality of life (see Ch. 4: Understanding Urban Carbon Fluxes, p. 189). Changes in land carbon stocks (either increases or decreases) can occur as co-effects of management for other products and values. For example, sound carbon cycle science could inform management options that might produce sustained co-benefits by considering the vulnerability of forests to disturbances (e.g., wildfires) and consequently focusing development of carbon sequestration activities in low-disturbance environments. An example trade-off in science-informed decision making is a management strategy to reduce the risk of severe wildfires in fire-prone areas that results in intentional, short-term reductions in ecosystem carbon stocks to reduce the probability of much larger reductions over the long term (see Ch. 9: Forests, p. 365). Likewise, management of wildfire regimes in vegetated landscapes can influence soil carbon storage via management effects on productivity and inputs of recalcitrant, pyrogenic (i.e., fire-produced) organic matter or black carbon in soils (see Ch. 12: Soils, p. 469). Protection of grasslands from conversion to croplands (e.g., in the Dakotas) can reduce emissions significantly. However, with high market prices for corn, carbon offsets alone cannot provide

enough economic incentive to retain grasslands (see Ch. 10: Grasslands, p. 399).

Leveraging Integrated Carbon Cycle Science

Local, state, provincial, and national governments in North America can benefit from scientific knowledge of the carbon cycle. When context and stakeholder involvement are considered, changes in technologies, infrastructure, organization, social practices, and human behavior are more effective. For example, the National Indian Carbon Coalition was established in the United States to encourage community participation in carbon cycle programs with the goal of enhancing both land stewardship and economic development on tribal lands. With the emergence of carbon markets as an option for addressing climate change, First Nations in Canada formed the "First Nations Carbon Collaborative" dedicated to enabling Indigenous communities to access and benefit from emerging carbon markets (see Ch. 7: Tribal Lands, p. 303).

Integrating data on societal drivers of the carbon cycle into Earth system and carbon cycle models improves representation of carbon-climate feedbacks and increases the usefulness of model output to decision makers. Better integrating research on Earth system processes, carbon management, and carbon prediction improves model accuracy, thereby refining shared representations of natural and managed systems needed for decision making (see Figure ES.6, p. 33, and Ch. 18: Carbon Cycle Science in Support of Decision Making, p. 728). Consequently, both carbon cycle science and carbon-informed decision making can be improved by increased interaction among scientists, policymakers, land managers, and stakeholders.

Conclusion and Progress Since SOCCR1

The conclusions from this report underscore the significant advances made in the understanding of the North American carbon cycle in the decade since SOCCR1 (CCSP 2007). Results show that emissions from the burning of fossil fuels for energy and other technological systems still represent the largest single source of the North American carbon budget. About 43% of these emissions are offset by terrestrial and coastal ocean sinks of atmospheric CO_2. A better understanding of inland waters is among the major scientific advances since SOCCR1 that are highlighted in this report. In contrast to SOCCR1, SOCCR2 clearly identifies a significant source of CO_2 from inland waters, as well as a similarly sized sink in the coastal ocean. This report also describes progress in documenting key elements of the CH_4 budget, which were largely absent in SOCCR1. Improved consistency between bottom-up inventories and top-down atmospheric measurements is encouraging for the design of future monitoring, reporting, and verification systems. Such systems will be enhanced greatly if uncertainties in the two approaches continue to decline as new measurement systems are deployed and as integrated analysis methods are developed. Importantly, understanding of the main causes of observed changes in the carbon budget has improved over the last decade, helping to establish a strong foundation for assessing options for reducing atmospheric carbon concentrations and for developing and using carbon management choices. Reducing carbon emissions from existing and future sources and increasing carbon sinks will need to involve science-informed decision-making processes at all levels: international, national, regional, local, industrial, household, and individual.

Despite improvements in calculating the carbon budget since SOCCR1, some regions and ecosystems still have highly uncertain estimates compared with others and thus need significant improvements in research and monitoring. Among these areas are Arctic and boreal regions, grasslands, tropical ecosystems, and urban areas. Also needed is a better overall understanding of the CH_4 cycle. The continued advancement of cross-disciplinary and cross-sectoral carbon cycle science to fill these gaps and to address the research challenges and opportunities identified in this report will be important for the third SOCCR to assess a decade from now.

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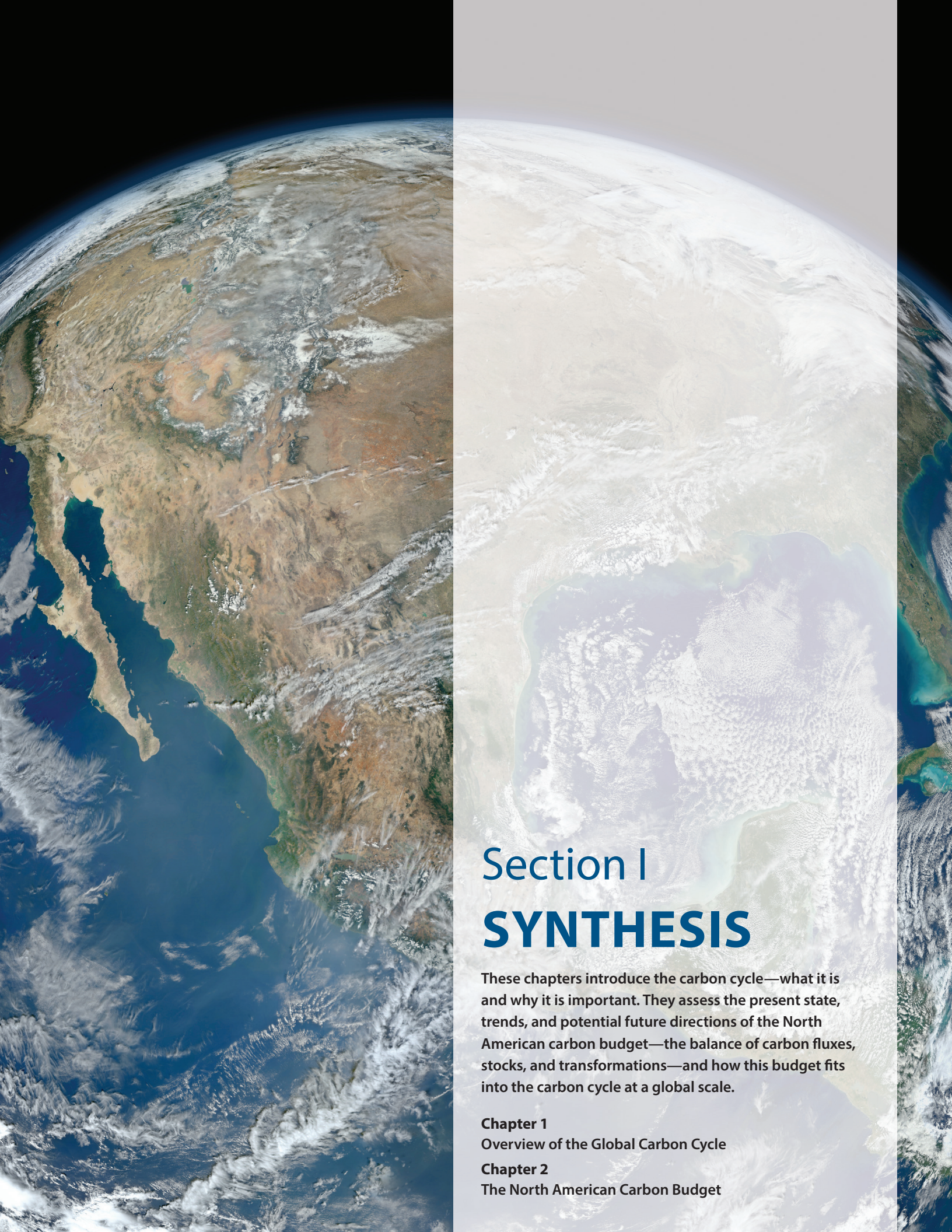

Section I
SYNTHESIS

These chapters introduce the carbon cycle—what it is and why it is important. They assess the present state, trends, and potential future directions of the North American carbon budget—the balance of carbon fluxes, stocks, and transformations—and how this budget fits into the carbon cycle at a global scale.

Chapter 1
Overview of the Global Carbon Cycle

Chapter 2
The North American Carbon Budget

1 Overview of the Global Carbon Cycle

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KEY FINDINGS

1. Atmospheric carbon dioxide (CO_2) has increased from a preindustrial abundance of 280 parts per million (ppm) of dry air to over 400 ppm in recent years—an increase of over 40%. As of July 2017, global average CO_2 was 406 ppm. Methane (CH_4) has increased from a preindustrial abundance of about 700 parts per billion (ppb) of dry air to more than 1,850 ppb as of 2017—an increase of over 160%. The current understanding of the sources and sinks of atmospheric carbon supports the dominant role of human activities, especially fossil fuel combustion, in the rapid rise of atmospheric carbon (*very high confidence*).

2. In 2011, the total global anthropogenic radiative forcing resulting from major anthropogenic greenhouse gases (GHGs, not including anthropogenic aerosols) relative to the year 1750 was higher by 2.8 watts per meter squared (W/m^2). As of 2017, the National Oceanic and Atmospheric Administration's Annual Greenhouse Gas Index estimates anthropogenic radiative forcing at 3.1 W/m^2, an increase of about 11% since 2011. In 2017, CO_2 accounted for 2.0 W/m^2 and CH_4 accounted for 0.5 W/m^2 of the rise since 1750. The global temperature increase in 2016 relative to the 1880 to 1920 average was over +1.25°C, although this warming was partially boosted by the 2015–2016 El Niño. Global temperature, excluding short-term variability, now exceeds +1°C relative to the 1880–1920 mean in response to this increased radiative forcing (Hansen et al., 2017; *very high confidence*).

3. Global fossil fuel emissions of CO_2 increased at a rate of about 4% per year from 2000 to 2013, when the rate of increase declined to about 2% per year. In 2014, the growth in global fossil fuel emissions further declined to only 1% per year (Olivier et al., 2016). During 2014, the global economy grew by 3%, implying that global emissions became slightly more uncoupled from economic growth, likely a result of greater efficiency and more reliance on less carbon intensive natural gas and renewable energy sources. Emissions were flat in 2015 and 2016 but increased again in 2017 by an estimated 2.0% (*high confidence*).

4. Net CO_2 uptake by land and ocean removes about half of annually emitted CO_2 from the atmosphere, helping to keep concentrations much lower than would be expected if all emitted CO_2 remained in the atmosphere. The most recent estimates of net removal by the land, which accounts for inland water emissions of about 1 petagram of carbon (Pg C) per year, indicate that an average of 3.0 ± 0.8 Pg C per year were removed from the atmosphere between 2007 and 2016. Removal by the ocean for the same period was 2.4 ± 0.5 Pg C per year. Unlike CO_2, CH_4 has an atmospheric chemical sink that nearly balances total global emissions and gives it an atmospheric lifetime of about 9 to 10 years. The magnitude of future land and ocean carbon sinks is uncertain because the responses of the carbon cycle to future changes in climate are uncertain. The sinks may be increased by mitigation activities such as afforestation or improved cropping practices, or they may be decreased by natural and anthropogenic disturbances (*high confidence*).

5. Estimates of the global average temperature response to emissions range from +0.7 to +2.4°C per 1,000 Pg C using an ensemble of climate models, temperature observations, and cumulative emissions (Gillett et al., 2013). The Intergovernmental Panel on Climate Change (IPCC 2013) estimated that to have a 67% chance of limiting the warming to less than 2°C since 1861 to 1880 will require cumulative emissions from all anthropogenic sources to stay below about 1,000 Pg C since that period, meaning that only 221 Pg C equivalent can be emitted from 2017 forward. Current annual global CO_2 emissions from fossil fuel combustion and cement production are 10.7 Pg C per year, so this limit could be reached in less than 20 years. This simple estimate, however, has many uncertainties and does not include carbon cycle–climate feedbacks (*medium confidence*). These conclusions are consistent with the findings of the recent *Climate Science Special Report* (USGCRP 2017).

Note: Confidence levels are provided as appropriate for quantitative, but not qualitative, Key Findings and statements.

1.1 The Role of Carbon in the Earth System

Carbon is an essential component of the Earth system. It is fundamental for the existence of life on Earth because of its ability to combine with other important elements, such as oxygen, nitrogen, and phosphorus, and with hydrogen to form the organic molecules that are essential for cellular metabolism and reproduction. Atmospheric carbon in the forms of carbon dioxide (CO_2) and methane (CH_4) helps regulate the Earth's climate by "trapping" heat in the atmosphere. This trapping of energy is known as the greenhouse effect, and CO_2 and CH_4, along with other greenhouse gases (GHGs) such as water vapor and nitrous oxide (N_2O), keep the Earth's climate in a habitable range. Carbon also is of significant socioeconomic importance because the burning of carbon-based fossil fuels is currently the dominant global means of energy production. Production and consumption of coal, oil, and natural gas release CO_2, CH_4, and other gases to the atmosphere. Considered in this chapter are the global carbon cycle and perturbations to it by human activities, as well as global climate–carbon cycle feedbacks and strategies to control or sequester emissions (see Box 1.1, Why a Global Carbon Cycle Context, this page).

In 2011, the total global radiative anthropogenic forcing (i.e., caused by humans) relative to the year 1750 was 2.8 watts per meter squared (W/m^2; Myhre et al., 2013). As of 2017, atmospheric observations of important radiatively active trace species (CO_2, CH_4, N_2O, CFC-11, CFC-12, and 15 minor halogenated gases) suggest that anthropogenic radiative forcing has risen to 3.1 W/m^2, an additional 11% (see Figure 1.1, p. 45).[1] The largest portion of this forcing, 2.0 W/m^2, is due to CO_2, with CH_4 accounting for 0.5 W/m^2. The global temperature in 2016 relative to the 1880 to 1920 average is greater by 1.25°C in response to this increased radiative forcing (Hansen et al., 2017). Other aspects of the climate system also are changing in response to the increased radiative forcing—the amount, distribution, and timing of rainfall, with extreme hydrological events becoming increasingly frequent, intense, and widespread (Hartmann et al., 2013). These changes may have significant effects on global food production. For example, currently productive regions may not be able to sustain agriculture in the future, especially if water availability becomes limited. Heat stress also can significantly affect agriculture, especially at tropical and subtropical latitudes but also at midlatitudes (Battisti and Naylor 2009). Even though CO_2 can result in increased terrestrial plant productivity (i.e., "CO_2 fertilization"), the negative impacts of climate change on agriculture are expected to dominate. In the ocean, the decrease in pH of ocean surface water is already about 0.1 pH unit (a decrease in pH of 7.5 to 7.4) since the start of the Industrial Revolution (Bates 2007). This increasing acidification of the ocean, along with water warming and pollution, endangers many marine organisms, including corals, shellfish, and

[1] National Oceanic and Atmospheric Administration Annual Greenhouse Gas Index. www.esrl.noaa.gov/gmd/ccgg/aggi.html.

Box 1.1 Why a Global Carbon Cycle Context

Although the focus of this report is on the state of the North American carbon cycle, this chapter provides a brief overview of the global carbon cycle. The North American budgets of carbon dioxide and methane must be put into the context of the global budgets. Carbon emissions from one region of the world are dispersed throughout the global atmosphere so that the radiative effects of regional emissions are global. Furthermore, influx of greenhouse gases from other parts of the world is a major contribution to the atmospheric greenhouse gas budgets of North America. Accurate estimates of the North American carbon budget depend on knowledge of contributions from the rest of the world, and hence globally distributed observations and knowledge of the global carbon budget is necessary.

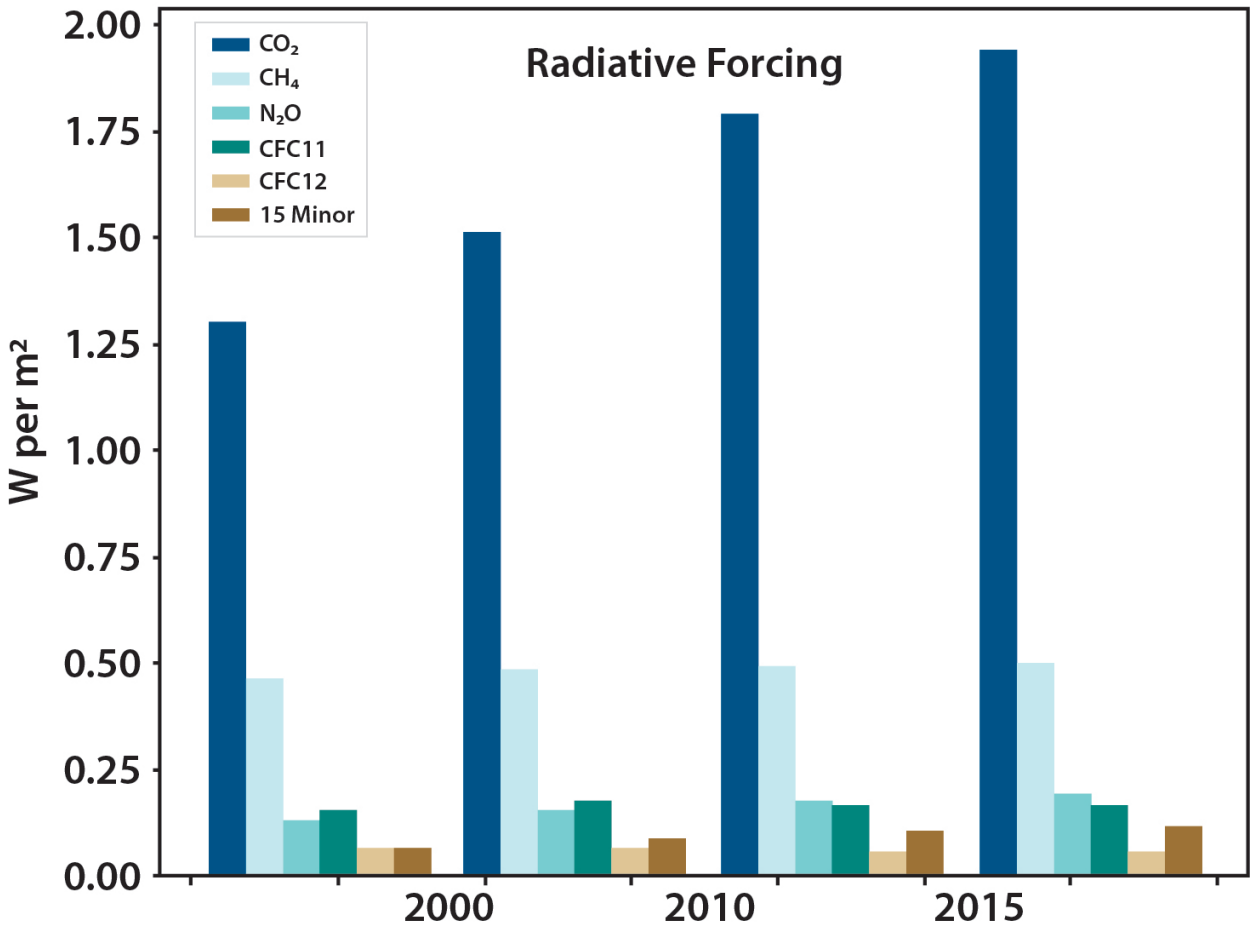

Figure 1.1. Radiative Forcing (Relative to 1750) Due to Major Greenhouse Gases (GHGs). Major GHGs include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), trichlorofluoromethane (CFC11), and dichlorodifluoromethane (CFC12). The 15 minor GHGs include CFC-113; CCl_4; CH_3CCl_3; HCFCs 22, 141b, and 142b; HFCs 134a, 152a, 23, 143a, and 125; SF_6; and halons 1211, 1301, and 2402. Radiative forcing calculations, in watts (W) per m^2, are based on measurements of GHGs in air trapped in snow and ice in Antarctica and Greenland prior to about 1980 and atmospheric measurements taken since then. [Figure source: Redrawn from National Academies of Sciences, Engineering, and Medicine 2018.]

marine plankton. Increasing CH_4 emissions can lead to tropospheric ozone formation, with implications for air quality (Fiore et al., 2002). Understanding and predicting future evolution of the global carbon cycle are critical for confronting these issues and, therefore, represent a challenging societal and scientific problem.

1.2 The Natural Carbon Cycle

In the Earth System, carbon is stored in rocks (as carbonates), sediments, ocean and freshwaters, soils and terrestrial biomass, and the atmosphere. By far the larger reservoir of carbon is the deep water of the ocean, which is thought to contain about 80% of the Earth System's carbon (excluding rock; see Figure 1.2, p. 46). Oceanic sediments are thought to contain 4%. Ocean surface waters and the atmosphere each hold about 2% of the Earth system's carbon reservoirs. Oil, gas, and coal reserves are thought to contribute another 3%. Soils and permafrost hold 5% and 4% of global carbon, respectively, while carbon stored in vegetation adds about 1%.

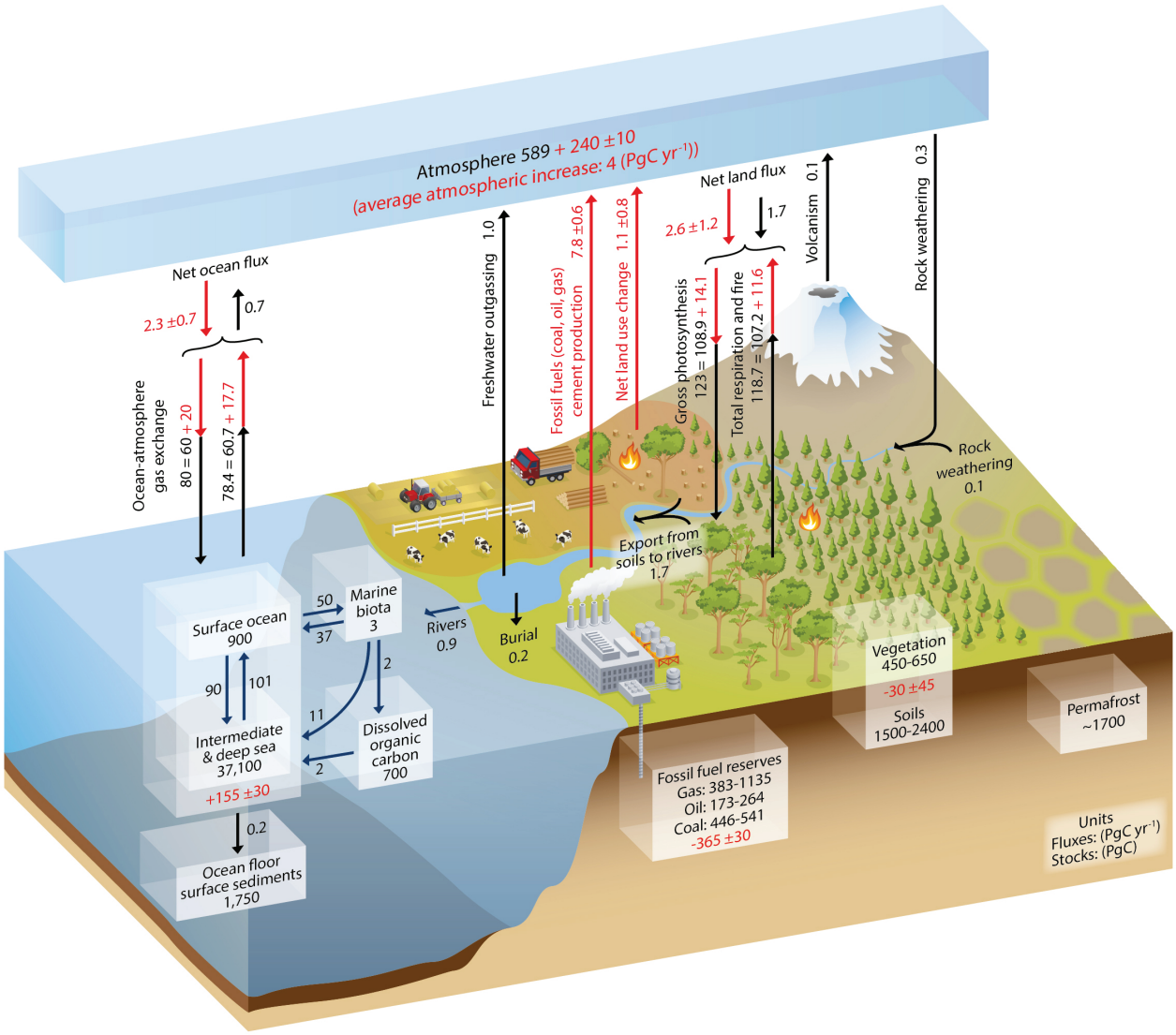

Figure 1.2. A Simplified Pictorial Illustration of the Global Carbon Cycle. The boxed numbers represent reservoir mass or carbon stocks in petagrams of carbon (Pg C). Arrows represent annual exchange (fluxes) in Pg C per year. Black numbers and arrows represent preindustrial reservoir masses and fluxes, while red arrows and numbers show average annual anthropogenic fluxes for 2000 to 2009. The red numbers in the reservoirs denote cumulative changes of anthropogenic carbon for the industrial period. Uncertainties are reported as 90% confidence intervals. [Figure source: Reprinted from Ciais et al., 2013, Figure 6.1. Copyright IPCC, used with permission.]

The global carbon cycle includes the mechanical, chemical, and biological processes that transfer carbon among these reservoirs (see Figure 1.2, this page). Reservoirs of carbon in the Earth system often are also referred to as "pools" or "stocks," and transfers of carbon between reservoirs are known as "fluxes." Some of these carbon fluxes are sensitive to climate, and their resulting responses to climate change are known as "carbon cycle–climate feedbacks." A positive feedback can occur when carbon fluxes to the atmosphere increase as a result of, for example, increasing temperatures. More carbon in the atmosphere leads to further climate warming, possibly further increasing carbon fluxes to the

atmosphere. Carbon cycle–climate feedbacks will be discussed further in Section 1.4, p. 56.

1.2.1 Carbon Dioxide

The global carbon cycle comprises a *fast* carbon cycle, having relatively rapid exchanges among the ocean, terrestrial biosphere, and atmosphere, and a *slow* carbon cycle, involving exchanges with geological reservoirs such as deep soils, the deeper ocean, and rocks. Equilibration between the terrestrial biosphere and ocean occurs on millennial timescales, while redistribution of CO_2 among geological reservoirs requires tens to hundreds of thousands of years or longer. Figure 1.2, p. 46, provides a pictorial representation of the exchanges of carbon among the main reservoirs, together with associated timescales.

Reservoirs for the fast components of the carbon cycle include the ocean, land vegetation and soils, freshwaters, shallow oceanic sediments, and the atmosphere. Based on estimates from the *Intergovernmental Panel on Climate Change Fifth Assessment Report* (IPCC AR5; IPCC 2013), about 830 petagrams of carbon (Pg C; 2000 to 2009 average) were present in the atmosphere, while 450 to 650 Pg C are stored in the terrestrial biosphere. Larger reservoirs of carbon exist in soils (1,500 to 2,400 Pg C; IPCC 2013), and soil organic carbon (SOC) densities are highest in moist boreal and tropical latitudes. Scharlemann et al. (2014) pointed out that these numbers are uncertain due to limited depth and sparse distribution of sampled or observed SOC profiles. The Arctic permafrost soils are estimated to contain 1,339 to 1,580 Pg C in the top 3 m of the soil column, with another 400 Pg C possible in deep soils (Schuur et al., 2015). Ocean waters and shallow sediments contain about 40,500 Pg C. The "fast-exchange" reservoirs of the ocean surface and marine biota hold only 900 Pg C and 3 Pg C, respectively. Turnover times for these fast- and slow-exchange reservoirs range from decades to millennia.

Exchange of carbon between the atmosphere and the terrestrial biosphere occurs via photosynthesis and respiration. Carbon is removed from the atmosphere by photosynthesis and fixed in leaves, roots, stems, and woody biomass. It is returned to the atmosphere through autotrophic (plant) respiration and heterotrophic (microbial) respiration of plant litter and soil carbon. Fire and other disturbances such as insect outbreaks and timber harvesting can be thought of as accelerated respiration processes, and the amount entering the atmosphere from these processes varies from year to year. Removal of CO_2 by photosynthesis is thought to have been slightly higher in the preindustrial atmosphere than emissions added from respiration and natural disturbances. Global total photosynthesis at that time is thought to have exceeded global respiration and emissions from natural disturbances so that net removal from the atmosphere by the land was about 1.7 Pg C per year. This removal is estimated to have been approximately in balance with outgassing from the ocean and freshwaters (Ciais et al., 2013; see Figure 1.2).

Gas exchange between the atmosphere and ocean depends on the difference between the partial pressure of CO_2 in surface water and that of CO_2 in the atmosphere (ΔpCO_2). Carbon dioxide dissolves in ocean water to form carbonic acid (H_2CO_3), which then forms bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}). These coupled reactions chemically buffer ocean water, thus regulating ocean pCO_2 and pH. Because pCO_2 can vary spatially, carbon outgasses from the ocean waters in some regions and is taken up in others. In regions where there is upwelling of nutrient-rich water and ocean waters are warm (e.g., in parts of the tropics), carbon is outgassed. In the North Atlantic, cold, sinking water removes carbon from the atmosphere. The Southern Ocean (latitudes south of 44°S) is another area where carbon is taken up. Carbon also is exchanged between land and ocean reservoirs via river transport to the coastal ocean.

Year-to-year variability of the global ocean CO_2 sink was thought to be small, at only about ±0.2 Pg C per year or 9% of annual ocean uptake (Wanninkhof et al., 2013); however, recent work by Landschutzer et al. (2016), based on comprehensive measurements of global ΔpCO_2 of ocean

surface water, suggests that substantial decadal and interannual variability can exist. They found that during the 1990s, the global ocean sink was likely to have been significantly smaller than after year 2000 (–0.8 ± 0.5 Pg C per year and –2.0 ± 0.5 Pg C per year, respectively). They proposed 1) that these decadal variations are driven by extratropics and are linked with the atmospheric northern and southern annular modes and 2) that interannual variability is driven by the tropical ocean. The variability of the global land sink is larger, varying by 3 to 4 Pg C per year, and most of this variability likely occurs in the tropics (Baker et al., 2006). This global atmospheric CO_2 interannual variability arises primarily from land sink variability because of the strong anticorrelation between CO_2 and $\delta^{13}C$ (e.g., Alden et al., 2010). Terrestrial net carbon exchange gives rise to significant $\delta^{13}C$ variability, whereas air-sea gas exchange does not. The El Niño Southern Oscillation (ENSO) is thought to be a significant driver of tropical carbon flux variability for both the ocean and terrestrial ecosystems. During the warm phase of ENSO, the ocean takes up more carbon because of reduced upwelling and outgassing from the eastern Tropical Pacific. On land, ENSO is associated with outgassing from the terrestrial biosphere, a phenomenon likely associated with drought and warmer global temperatures. Indeed, the strong ENSO of 2016 pushed measured CO_2 concentrations at Mauna Loa to above 400 ppm, where they have remained (Betts et al., 2016).

The slow, or geological, carbon cycle operates on timescales of tens of millennia and longer. Fluxes to the atmosphere from volcanism, CO_2 removal from the atmosphere by chemical weathering, and ocean sediment formation together are a factor of 10 smaller than the fluxes of the fast carbon cycle. A vast amount of carbon is also stored in sedimentary rocks (100×10^6 Pg C), with an estimated 4,000 Pg C stored as hydrocarbons (Ciais et al., 2013).

Ice core evidence suggests that during glacial periods atmospheric CO_2 was present at about 180 to 200 ppm. During interglacial periods, atmospheric CO_2 abundance was higher, between 270 to 290 ppm (Lüthi et al., 2008; Petit et al., 1999). The current atmospheric levels of 400 ppm are well outside the range that existed during the period resolved by ice cores; that is, 800,000 years before present. The most recent glacial period ended about 12,000 years ago, with the most recent glacial maximum occurring about 22,000 years ago. Even older evidence from Arctic lake sediments suggests that around 3.5 million years ago, Arctic summer temperatures were about 8°C warmer than today with atmospheric CO_2 levels around 400 ppm (Brigham-Grette et al., 2013). Contemporary CO_2 has surpassed 400 ppm, suggesting that the current Arctic is not yet in equilibrium with rapidly rising greenhouse gas concentrations and may become much warmer in the future.

Estimates for recent decades show significant trends and variability in the main components of the global carbon cycle (see Table 1.1, p. 49). Only about half of human-driven emissions from fossil fuel burning, industry (e.g., cement manufacturing), and land-use change remains in the atmosphere, although the growth in atmospheric CO_2 is highly variable depending on emissions and the strength of uptake by land and ocean (see Table 1.1). Emissions have risen by about 70% from the 1980s to the most recent decade (2007 to 2016), while land and ocean have taken up 3.0 ± 0.8 and 2.4 ± 0.5 Pg C per year, respectively (Le Quéré et al., 2017). Of this amount, North America represents a rather substantial share of global carbon uptake (0.31 Pg C per year; see Ch. 2: The North American Carbon Budget, p. 71). Figure 1.3a, p. 50, shows global average atmospheric CO_2 derived from *in situ* surface air samples. The steep rise in CO_2 reflects anthropogenic emissions, while the annual cycle reflects the seasonal uptake of vegetation, predominantly in the Northern Hemisphere.

1.2.2 Methane

Total global CH_4 emissions are approximately 550 teragrams (Tg) of CH_4 per year (1 Tg CH_4 per year = 10^{12} grams of CH_4 per year; Saunois et al., 2016). Of this, roughly 40% comes from natural sources. The largest (and most uncertain) natural

Table 1.1. Historic[a] and Decadal[b] Global Mean Emissions and Their Partitioning to the Carbon Reservoirs of Atmosphere, Ocean, and Land

	1750–2011 Cumulative Pg C[c]	1980–1989 Pg C per Year	1990–1999 Pg C per Year	2000–2009 Pg C per Year	2007–2016 Pg C per Year	2016 Pg C per Year
Emissions						
Fossil Fuels and Industry	375 ± 30	5.5 ± 0.3	6.3 ± 0.3	7.8 ± 0.4	9.4 ± 0.5	9.9 ± 0.5
Land-Use Change	180 ± 80	1.2 ± 0.7	1.3 ± 0.7	1.2 ± 0.7	1.3 ± 0.7	1.3 ± 0.7
Partitioning to Carbon Reservoir						
Growth in Atmospheric CO_2[c]	240 ± 10	3.4 ± 0.1	3.1 ± 0.1	4.0 ± 0.1	4.7 ± 0.1	6.0 ± 0.2
Ocean Uptake	160 ± 80	1.7 ± 0.5	1.9 ± 0.5	2.1 ± 0.5	2.4 ± 0.5	2.6 ± 0.5
Land Uptake	155 ± 30	2.0 ± 0.6	2.5 ± 0.5	2.9 ± 0.8	3.0 ± 0.8	2.7 ± 0.9

Notes

a) Historic cumulative emissions and partitioning from the *Intergovernmental Panel on Climate Change Fifth Assessment Report* (Ciais et al., 2013).

b) Decadal means from the Global Carbon Project (Le Quéré et al., 2017).

c) Pg C, petagrams of carbon; CO_2, carbon dioxide.

emissions of CH_4 are from wetlands, defined as regions that are permanently or seasonally waterlogged. Natural wetlands include high-latitude bogs and fens, tropical swamps, and temperate wetlands. Saturated soils in warm tropical environments tend to produce the most CH_4. However, warming Arctic temperatures raise concerns of increasing emissions from high-latitude wetlands and future decomposition of carbon currently stored in frozen Arctic soils (e.g., Schaefer et al., 2011; Schuur et al., 2015). Figure 1.4, p. 51, provides a pictorial representation of the main components of the global methane cycle.

Estimates of global CH_4 emissions from wetlands range from 127 to 227 Tg CH_4 per year (Saunois et al., 2016), with most probable values between 167 and 185 Tg CH_4 per year. Most emissions occur in tropical regions (Matthews 1989; Melton et al., 2013; Saunois et al., 2016). Currently, only about 25 Tg CH_4 per year (i.e., 4% of global emissions) are thought to be emitted from high northern latitudes (AMAP 2015; Saunois et al., 2016). Because emissions are sensitive to temperature and precipitation, they exhibit significant seasonal cycles, especially at high latitudes, as well as interannual variability caused by moisture and temperature variability. Smaller amounts of CH_4 are emitted from fires, the ocean, and enteric fermentation in termites and wild animals (20 Tg CH_4 per year or less for each). In addition, up to 60 Tg CH_4 per year may be emitted from geological sources, such as seeps, clathrates, mud volcanoes, and geothermal systems (Etiope et al., 2008; Schwietzke et al., 2016).

Unlike CO_2, CH_4 has an atmospheric chemical sink that nearly balances total global emissions. Removal of atmospheric CH_4 by reaction with the hydroxyl radical (OH) results in a CH_4 atmospheric lifetime of about 9 to 10 years. Observationally constrained estimates of CH_4 lifetime suggest either small decreases of about 2% from 1980 to 2005 (Holmes et al., 2013) or stable CH_4 lifetimes with the possibility of interannual variability of about 2% (Montzka et al., 2011). CH_4 is a much more powerful greenhouse gas than CO_2 (on a per mass basis and over 100 years, CH_4 is about 25 times more effective at trapping heat than CO_2).

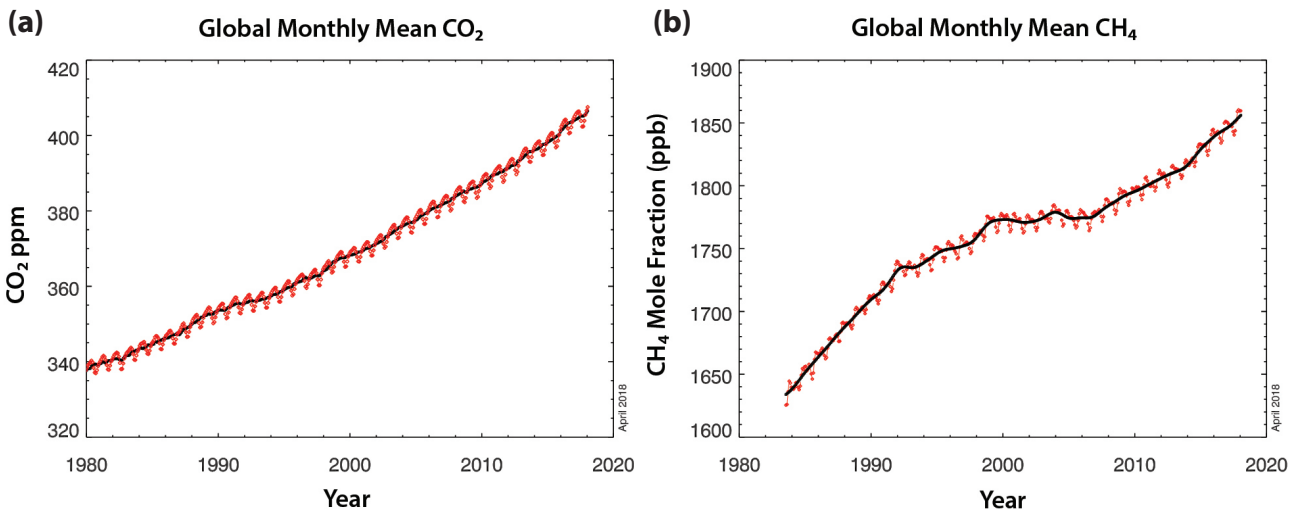

Figure 1.3. Global Averages of Atmospheric Gases Derived from Surface Air Samples. (a) Carbon dioxide (CO_2) in parts per million (ppm). **(b)** Methane (CH_4) in parts per billion (ppb). [Figure source: Redrawn from NOAA-ESRL-GMD 2017.]

As shown in Figure 1.3b, this page, atmospheric CH_4 increased rapidly during the 1980s and early 1990s before its growth leveled off between the mid-1990s and early 2000s. Methane has resumed its increase in the atmosphere since 2006, and observations show that this growth has even accelerated since 2014. The changing atmospheric CH_4 growth rate has been the subject of much debate, questioning why growth rate slowed for a decade starting in the mid-1990s. Several studies suggested that this slower rate was due to decreases in fugitive emissions from fossil fuel production (Aydin et al., 2011; Simpson et al., 2012) or to decreased emissions from anthropogenic microbial sources, such as rice agriculture (Kai et al., 2011). On the other hand, Dlugokencky et al. (1998, 2003) proposed that the slowing of CH_4 growth in the atmosphere was due to an approach to a quasi–steady state, reached when global sources and sinks are in balance. Consistent with this view, the study of Schwietzke et al. (2016) found that emissions from oil and gas production have remained stable over the past several decades, implying increasing efficiency in fossil fuel production industries while their production was increasing over time.

Dlugokencky et al. (2003) predicted that CH_4 would approach a steady state in the atmosphere of about 1,780 ppb by the 2010s if there were no major changes in its budget. The methane budget did change, however, because the atmospheric growth of CH_4 resumed its rise in 2006. The cause of the recent increase in CH_4 growth also has been much debated. Based on global observations of the CH_4 isotope, $^{13}CH_4$, the global growth in CH_4 appears likely to have been dominated by microbial sources in the tropics (wetlands or agriculture and waste), rather than fossil fuel production (Nisbet et al., 2016; Schaefer et al., 2016), as suggested by some studies (e.g., Rice et al., 2016). Other studies have argued that $^{13}CH_4$ may not be a very strong constraint on the global methane budget and that changes in the atmospheric CH_4 chemical sink are responsible for the global methane changes (Rigby et al., 2017; Turner et al., 2017). However, plausible chemical mechanisms that could explain the changes in the CH_4 sink have not been identified. Using space-based retrievals of carbon monoxide, Worden et al. (2017) argued that the isotopic data record also can be consistent with increased fossil fuel emissions if global biomass-burning emissions have decreased twice as much as estimates based

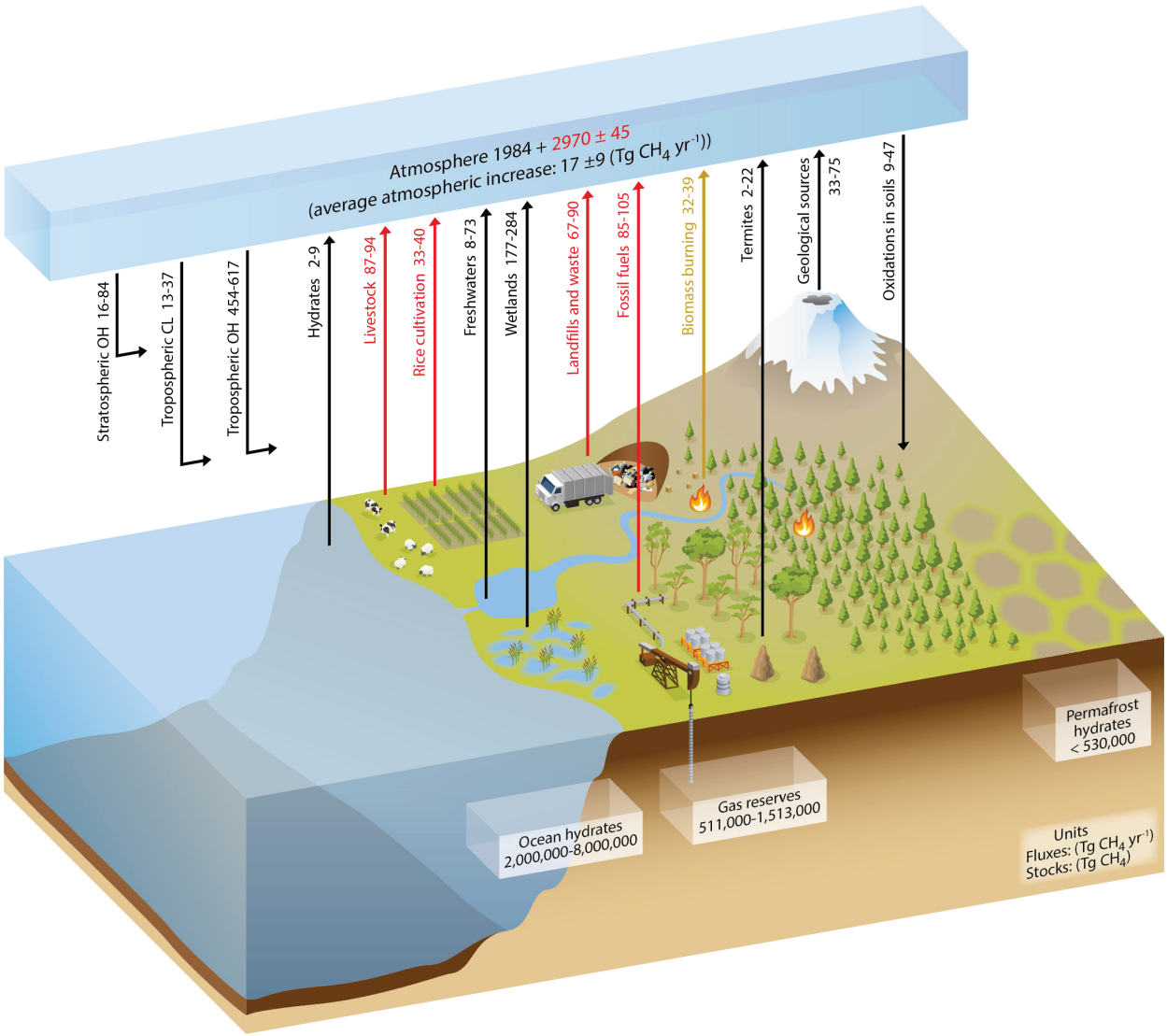

Figure 1.4. A Pictorial Illustration of the Global Methane (CH_4) Cycle. The arrows and boxed numbers represent annual fluxes in teragrams (Tg) of CH_4 per year estimated from 2000 to 2009 and CH_4 reservoirs in Tg CH_4. Reservoirs include the atmosphere and three geological reservoirs (i.e., hydrates on land and in the ocean floor and gas reserves). The black arrows show natural emissions, while red arrows show anthropogenic fluxes. The brown arrow represents total anthropogenic and natural emissions. [Figure source: Reprinted from Ciais et al., 2013, Figure 6.2. Copyright IPCC, used with permission.]

on space-based observations of burned areas. If the recent rise of global atmospheric CH_4 is indeed due to increases in microbial emissions, then the question becomes whether anthropogenic or natural microbial sources are responsible. Some studies have suggested that anthropogenic microbial sources, such as livestock, are behind the increased atmospheric growth of CH_4 (Schaefer et al., 2016; Saunois et al., 2016). If the increase is due to emissions from wetlands, especially in the tropics, then this raises the possibility that changing climate could be changing natural emissions.

1.3 Perturbations to the Global Carbon Cycle

The carbon cycle undergoes perturbations caused by a variety of natural processes such as wildfires, droughts, insect infestations, and disease. These processes can themselves be affected by human activities, for example through GHG emissions that change climate, wildfire suppression, and land-use change. During longer periods, variations in the Earth's orbit also drive significant perturbations to the global carbon cycle. Over the recent several centuries, human activity has resulted in perturbations to the carbon cycle that have no precedent in geological records. Anthropogenic emissions also can directly alter the chemistry of the atmosphere, possibly affecting its ability to remove pollutants. These human-caused carbon cycle perturbations are discussed in this section.

Since the dawn of the Industrial Age over 250 years ago, humans have significantly altered the global carbon cycle, chiefly by combustion of fossil fuels, but also by perturbing the natural carbon cycle. An example is the large-scale conversion of forests to agricultural land and rangeland. As a result, atmospheric concentrations of CO_2 and CH_4 have increased dramatically. Atmospheric CO_2 has increased from a preindustrial abundance of 280 ppm of dry air (MacFarling Meure et al., 2006) to more than 400 ppm in recent years (NOAA-ESRL-GMD Trends 2017),[2] an increase of 43%. Methane has increased from a preindustrial abundance of about 700 ppb of dry air to current values of over 1,850 ppb, an increase of over 160%. Current understanding of the sources and sinks of atmospheric carbon supports the dominant role played by human activities, especially fossil fuel combustion, in the rapid rise of atmospheric carbon. For example, Tans (2009) demonstrated that accumulated carbon in the atmospheric and oceanic reservoirs since preindustrial times is approximately equivalent to the total amount emitted by fossil fuel combustion. If fossil fuel emissions were abruptly terminated, 20% to 40% of this carbon would remain airborne for millennia (Archer et al., 2009; Archer and Brovkin 2008; Solomon et al., 2009). Increases in atmospheric carbon, along with smaller contributions from other GHGs emitted by humans, have led to annual global mean temperatures that have risen by 0.85°C during 1880 to 2012 (IPCC 2013). If recent years are included, the global average temperature has increased by about 1.25°C since 1880 (Hansen et al., 2017).

1.3.1 Anthropogenic Emissions

By burning coal, oil, and gas, humans are accelerating the part of the geological carbon cycle that transfers carbon in rocks and sediments to the atmosphere. From 1870 to 2017, humans emitted 430 ± 20 Pg C as CO_2 to the atmosphere (Le Quéré et al., 2018). Global fossil fuel emissions of CO_2 increased at a rate of about 4% per year from 2000 to 2012, when emissions growth decreased to about 1% per year. In subsequent years, the growth of CO_2 emissions continued to decline, leveling off in 2015 (see Figure 1.4, p. 51; Le Quéré et al., 2018), when global carbon emissions from fossil fuel use and cement production—an industry which releases CO_2 as a by-product of the chemical process that produces lime from limestone—was estimated to total 9.9 Pg C (about 100 times faster than natural geological fluxes; see Figure 1.2, p. 46). This leveling off of emissions occurred even as the global economy was expanding (see Figure 1.5, p. 53). In 2017, global CO_2 emissions rose again by an estimated 2%, likely due to faster economic growth and lower fossil fuel prices (Le Quéré et al., 2018).

Humans also can affect the global carbon cycle through land-use change, mainly by conversion of forests to agricultural land. Often deforestation is accomplished through use of fire. Emitted during the land-use conversion process from forest to other uses, CO_2 thereafter reduces carbon uptake. Reforestation of formerly agricultural land can cause increased carbon uptake over time. Cumulative emissions of carbon from land-use change (mainly

[2] National Oceanic and Atmospheric Administration Global Monitoring Division, Trends in Atmospheric Carbon Dioxide; esrl.noaa.gov/gmd/ccgg/trends/global.html.

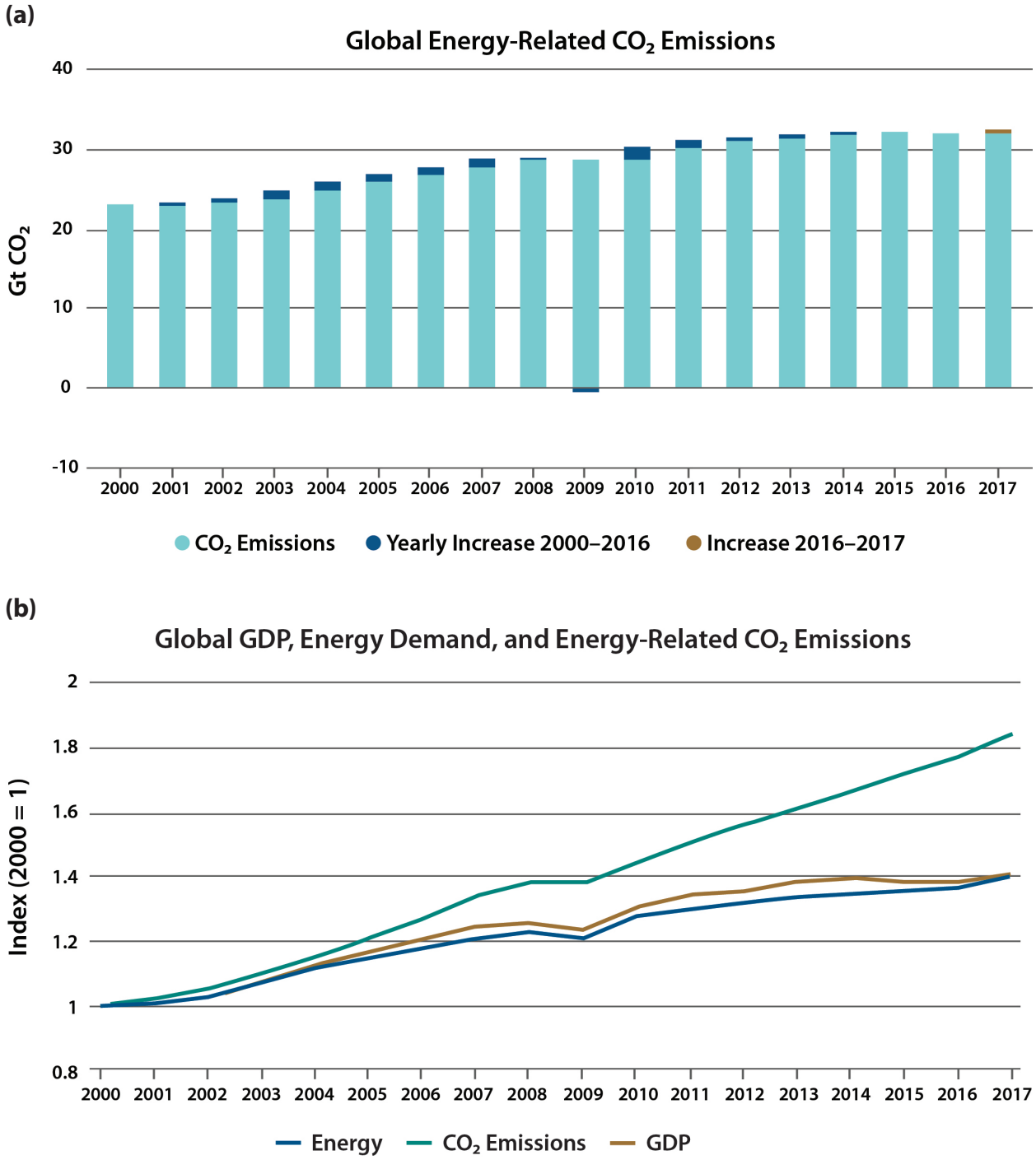

Figure 1.5. Global Energy-Related Carbon Dioxide (CO_2) Emissions. (a) Fossil fuel CO_2 emissions in gigatons (Gt) and their yearly increase. **(b)** Growth in CO_2 emissions, energy demand, and global gross domestic product (GDP) normalized to 2000. [Figure source: Redrawn from International Energy Agency (IEA) data in the *Global Energy & CO_2 Status Report 2017* (IEA 2017). Copyright Organisation for Economic Cooperation and Development/ IEA, used with permission.]

clearing of land for agriculture) since 1750 are estimated at 225 ± 75 Pg C (Le Quéré et al., 2018).

Atmospheric CH_4 also is influenced by diverse human activities, ranging from food production (e.g., ruminants and rice) to waste (e.g., sewage and landfills) to fossil fuel production (e.g., coal, oil, and gas). Future increases in population likely will increase CH_4 emissions from agriculture and waste as demand rises for more food production. Furthermore, the current boom in shale oil and gas exploitation has focused attention on leakage from drilling, storage, and transport of fossil fuel (e.g., Peischl et al., 2015; Pétron et al., 2014). Chemical reaction with OH accounts for about 90% of the total CH_4 sink (Ehhalt 1974). These OH radicals, produced through the photolysis of ozone (O_3) in the presence of water vapor, are destroyed by reactions with CH_4 and other compounds. Uncertainty in the sink due to chemical loss by OH is 10% to 20%, because the OH distribution remains uncertain at regional to global scales (Saunois et al., 2016).

Relative to CO_2, CH_4 and other short-lived climate forcers such as black carbon have short atmospheric lifetimes; thus, estimates project that their mitigation potentially could reduce global mean warming by about 0.5°C by 2050, with air quality and agricultural productivity as co-benefits. Such mitigation, however, would not significantly limit maximum warming beyond 2050 (Shindell et al., 2012; Rogelj et al., 2014; National Academies of Sciences, Engineering, and Medicine 2018). Various strategies are possible for reducing emissions or enhancing the CH_4 sink. For example, some increases in agricultural and waste emissions possibly could be avoided through improved practices and changed dietary trends (Hall et al., 2009; see Ch. 5: Agriculture, p. 229, for more information on agricultural and food emissions). In addition, humans potentially can alter the chemical lifetime of CH_4 through emissions that affect the abundance of OH. Naik et al. (2013) found that OH might be about 10% lower than in preindustrial times, although with large uncertainty.

Current estimates reported by Saunois et al. (2016) for anthropogenic emissions average 328 Tg CH_4 per year (ranging from 259 to 370 Tg CH_4 per year). Extraction and processing of fossil fuels account for 32% to 34% of all anthropogenic emissions. Livestock, agriculture, landfills, and sewage together account for another 55% to 57%, with the remainder due to biomass and biofuel burning. A recent study using observations of the isotopic composition of CH_4 suggests that emissions from fossil fuel production and geological emissions may be 20% to 60% higher than previously thought. This increase would require a compensating reduction in microbial emissions from natural and anthropogenic sources (Schwietzke et al., 2016) for the atmosphere to be in balance with the observed global average CH_4 abundance.

Current CH_4 levels are unprecedented in over at least 800,000 years (Loulergue et al., 2008). Recent National Oceanic and Atmospheric Administration atmospheric network observations have shown that global CH_4 increased rapidly through the late 1990s, leveled off during the early 2000s, and began to increase again in 2007 (Dlugokencky et al., 2009; Rigby et al., 2008). These changes in global CH_4 are not well understood and are under debate. Although Dlugokencky et al. (1998, 2003) suggested that the plateau in CH_4 growth resulted from an approximate balance between global sources and sinks, some studies suggested that decreases in anthropogenic emissions (Aydin et al., 2011; Kai et al., 2011; Simpson et al., 2012) led to the period of slow CH_4 growth. Isotopic evidence points toward increased emissions from microbial sources as an explanation for the recent rise in global CH_4 (Nisbet et al., 2016; Schaefer et al., 2016; Schwietzke et al., 2016). However, increases in anthropogenic emissions also have been proposed (Rice et al., 2016), as well as decreases in the chemical loss (Rigby et al., 2017; Turner et al., 2017). Worden et al. (2017) have recently suggested a significant role for fossil fuel emissions in the recent growth of atmospheric CH_4 based on decreases in biomass burning that could change the interpretation of methane isotope observations. This result is based on space-based

observations of atmospheric CO, which itself may be responding to changes in other sources besides biomass burning.

Figure 1.1, p. 45, shows that CH_4 contributed just over 0.5 W/m^2 in 2017 to global total anthropogenic radiative forcing, an amount which is about one-fourth of that from CO_2. Although CH_4 is much more effective at absorbing infrared radiation (Hofmann et al., 2006; Myhre et al., 2013),[3] it is about a hundred times less abundant in the atmosphere than CO_2.

1.3.2 North American Emissions in a Global Context

Historically, North America has been one of the world's largest producers of human-caused CO_2 emissions. Between 1850 and 2011, the United States has added 27% of the cumulative emissions, compared with 25% from European Union (EU) countries and 11% from China, currently the world's largest emitter (World Resources Institute et al., 2014).[4] In 2015, North America emitted almost 15% (1.5 Pg C) of the 9.9 Pg C emitted globally (Olivier et al., 2016). Of North America's annual total emissions, a majority (84%) came from the United States, while Canada and Mexico emitted 8.7% and 7.3%, respectively. Since the 2007 publication of the *First State of the Carbon Cycle Report* (SOCCR1), China has replaced the United States as the world's top emitter of CO_2, adding 2.8 Pg C to the atmosphere in 2014, about twice U.S. emissions (Olivier et al., 2016). In terms of cumulative emissions, the United States is responsible for 100 Pg C out of a global total of 378 Pg C (UNFCCC 2013; World Resources Institute 2017). If land-use change and forestry are taken into account, U.S. contributions have totaled 134 Pg C out of a global total of 572 Pg C of net emissions. For comparison, historical emissions (including land-use change and forestry) of EU countries and China are 114 and 74 Pg C, respectively.

Both inventory (i.e., field measurements) and modeling techniques have been used to estimate land-based carbon sinks for North America (King et al., 2015). These estimates show that human-caused carbon emissions in North America are significantly higher than the land's capacity to absorb and store them. For example, estimates suggest that between 2000 and 2009, only 15% to 49% (with a mean estimate of 26%) of North American fossil fuel emissions were absorbed by North American lands (King et al., 2015). As a result, North America is considered to be an overall net source of carbon to the atmosphere. However, the ability of North American land to take up and store carbon is significant. Globally, estimates suggest that over the past decade (2006 to 2015) 2.4 ± 0.5 Pg C per year were taken up by the ocean and 3.0 ± 0.8 Pg C per year were taken up by the terrestrial biosphere (Le Quéré et al., 2017). Of these totals, the amount taken up by the terrestrial biosphere in North America is estimated to be about 0.47 Pg C per year (King et al., 2015), or 15% of global terrestrial uptake.

Carbon uptake by North American lands is driven largely by the regrowth and recovery of forests from earlier human-driven changes in land cover and land use, such as forest clearing and harvesting (King et al., 2015), as well as increases in forest area from improved forest management practices (Melillo et al., 2014). Environmental influences on plant growth, such as the fertilizing effects of rising concentrations of atmospheric CO_2 and nitrogen, along with changes in climate including longer growing seasons in northern midlatitude regions also have contributed to increased carbon uptake in North America over the past two decades (King et al., 2015; Melillo et al., 2014; see Ch. 2: The North American Carbon Budget, p. 71).

However, the emissions of other GHGs, primarily CH_4 and N_2O, partially offset the potential climate cooling induced by the uptake of CO_2 in North America (Tian et al., 2016). North America accounts for about 10% of natural (e.g., wetlands) and 12% of human-driven (e.g., agriculture and fossil

[3] Hofmann et al. (2006), updated at www.esrl.noaa.gov/gmd/aggi/.

[4] World Resources Institute, wri.org/blog/2014/11/6-graphs-explain-world's-top-10-emitters/.

fuels) global CH_4 emissions (Kirschke et al., 2013; see Ch. 2: The North American Carbon Budget).

1.4 The Future Carbon Cycle: Emissions, Sinks, and Carbon Cycle–Climate Feedbacks

Coupled carbon cycle–climate models forced with future "business as usual" emissions scenarios suggest that the changing carbon cycle will be a net positive feedback on climate, reinforcing warming, but the size of the projected feedback is highly uncertain (Friedlingstein et al., 2014). Besides the uncertain trajectories of human factors such as fossil fuel emissions, land use, or significant mitigation efforts, various natural processes can lead to the carbon cycle being a positive feedback. For example, a warming climate can lead to increased fires and droughts and less storage of carbon in the terrestrial biosphere. In particular, warming is expected to decrease carbon uptake in the tropics and midlatitudes. In the high latitudes, a warmer climate is expected to lead to a more productive biosphere and more uptake but also may result in increased respiration and release of stored CO_2 and CH_4 in soils and lakes. Negative feedbacks also are possible, such as increased atmospheric CO_2, leading to increased carbon storage in the terrestrial biosphere (e.g., Schimel et al., 2015), although the relative roles of this effect relative to land-use change, nitrogen deposition, and temperature increases on the cumulative land carbon sink over the last century are not fully understood (Huntzinger et al., 2017).

Human impacts on land use can directly impact climate. Deforestation and agriculture can affect carbon storage in soil and biomass. Fertilizer use also affects the global nitrogen budget and can increase carbon storage. Large-scale drainage of wetlands and conversion to agricultural land can reduce CH_4 emissions from anaerobic respiration while potentially increasing faster soil carbon loss through aerobic respiration.

The ocean carbon sink is driven primarily by the partial pressure difference of CO_2 between the atmosphere and the ocean surface (ΔpCO_2). Although this mechanism would imply that increasing atmospheric CO_2 concentrations would, therefore, lead to increased uptake of CO_2 in the ocean, there actually is substantial uncertainty in future uptake due to uncertainty in future changes to ocean circulation, warming, and chemical changes, all of which would impact the ocean sink (Lovenduski et al., 2016; Randerson et al., 2015). In addition, the sequestration of CO_2 in ocean water also can lead to undesirable impacts as the ocean becomes more acidic. For example, ocean acidification disrupts the ability of organisms to build and maintain calcium carbonate ($CaCO_3$) shells, substantially perturbing ocean ecosystems.

Frozen Arctic soils compose another potential carbon cycle–climate feedback (see Ch. 11: Arctic and Boreal Carbon, p. 428, and Ch. 19: Future of the North American Carbon Cycle, p. 760). An estimated 1,460 to 1,600 Pg C are frozen in Arctic soils, and warming has proceeded in the Arctic faster than in any other region. Current understanding suggests that approximately 146 to 160 Pg C, primarily as CO_2, could be vulnerable to thaw and release to the atmosphere over the next century (Schuur et al., 2015; see Ch. 11: Arctic and Boreal Carbon). This release of carbon from permafrost is likely to be gradual and occur on century timescales (Schuur et al., 2015). If the amount of carbon estimated to enter the atmosphere by Schuur et al. (2015) were released annually at a constant rate, emissions would be far lower than annual fossil fuel emissions (about 9 Pg C per year) but comparable to land-use change (0.9 Pg C per year).

Factors that will affect the carbon cycle are explored in much more depth in respective chapters of this report, and Ch. 19 describes future projections and the results of different IPCC scenarios on the North American carbon cycle in a global context.

1.5 The Carbon Cycle and Climate Mitigation

Concern about the effects of climate change, on the one hand, and the difficulties of reducing emissions

of carbon from fossil fuel use, on the other, have led to a target of limiting global average warming to no more than 2°C, with a more conservative target of 1.5°C to reduce the risks of the most serious effects of climate change (USGCRP 2017). The choice of 2°C reflects a balance between a realistic threshold and one that would result in a presumably tolerable amount of climate change. However, as Knutti et al. (2015) points out, no proof exists that this threshold maintains a "safe" level of warming, and the definition of "safe," as well as the components of the Earth system that the term applies to, are themselves subjective. Several recent studies have suggested that the accumulated carbon in the atmosphere already may have committed the climate system to 2°C or more of global average temperature increase (Mauritsen and Pincus 2017; Raftery et al., 2017).

The relationship of cumulative carbon emissions to global temperature increase depends on the data constraints or model used to simulate the temperature response. Gillett et al. (2013) reports an observationally constrained range of 0.7 to 2.0°C per 1,000 Pg C (5% to 95% confidence interval) and a range of 0.8 to 2.4°C per 1,000 Pg C based on 15 models from the Coupled Model Intercomparison Project Phase 5 (CMIP5). Similarly, IPCC (2013) estimates that limiting the warming with a probability of >33%, >50%, and >67% to less than 2°C since the period 1861 to 1880 will require cumulative emissions from all anthropogenic sources to stay below about 1,570 Pg C, 1,210 Pg C, and 1,000 Pg C since that period, respectively. Cumulative emissions since 1850, including land-use change and forestry, are 572 Pg C (Global Carbon Project 2016; Peters et al., 2015; World Resources Institute 2017). However, this amount includes only the carbon from CO_2 emissions and does not include non-CO_2 emissions (i.e., primarily CH_4 and N_2O), which amount to an additional 210 Pg C equivalent from non-CO_2 sources, bringing the total to 779 Pg C equivalents (Peters et al., 2015). This amount implies that, to achieve a >33%, >50%, and >67% warming probability limited to below 2°C, amounts of no more than 791, 431, or 221 Pg C equivalent, respectively, can be emitted from 2017 forward. Current annual global emissions of CO_2 from fossil fuel combustion and cement production are 10.7 Pg C per year (Le Quéré et al., 2017), so this limit could be reached in less than 80, 40, or 20 years. Although technically achievable (Millar et al., 2017), the most conservative emissions reductions would require immediate and concerted action.

These simple estimates of cumulative emissions and their effect on future global temperature, however, have many uncertainties. Uncertainties in climate models include cloud, aerosol, and carbon cycle feedbacks. Carbon-climate feedbacks, such as the effect on carbon emissions from permafrost thaw, are highly uncertain and may significantly lower the cumulative amount of carbon that can be emitted before exceeding the 2°C global temperature increase.

Attempts to avoid the most severe impacts of climate change through management of the carbon cycle rely on reducing emissions and increasing storage in land and ocean reservoirs. Other means that focus on adaptation are not specifically addressed in this report. Evaluating and predicting the success of these strategies require an understanding of all the natural and anthropogenic components of the global carbon cycle because decreases in emissions or increases in sinks from mitigation activities may be offset partially or wholly by changes in other components. Globally, land and ocean sinks have averaged between 3.9 and 4.7 Pg C per year since 2000 (Le Quéré et al., 2016), growing over time in proportion to emissions (Ballantyne et al., 2012). The sink on land, accounting recently for about 25% of total emissions (Le Quéré et al., 2016), is consistent with the measured increase in carbon stocks of forests (Pan et al., 2011). In North America, the forest sink is currently about 223 Tg C per year (see Ch. 9: Forests, p. 365), but increases in the frequency of wildfires and insect infestations in the western continent threaten to reduce that sink. The sink in Canadian forests, though much smaller than that in the United States, also is threatened by insects and wildfire and could become a significant source (Kurz et al., 2013), as has happened recently. Mexican forests also are thought to be a small sink

based on estimates of regrowth of previously disturbed forests that exceed emissions from deforestation and forest degradation (see Ch. 9: Forests, p. 365).

Options for managing emissions of carbon and other GHGs include 1) reduction or cessation of the use of fossil fuels, replacing them with renewable sources of energy (e.g., solar, wind, and water); 2) climate intervention via carbon dioxide removal (CDR), including carbon capture and storage (CCS), which involves absorption of emissions at point sources; and 3) negative emissions, using approaches to remove previously emitted CO_2 by increasing storage in terrestrial and ocean reservoirs. Climate intervention via albedo modification does not affect the carbon budget directly but is an attempt to counteract climate change by directly influencing the global radiation balance. For example, introducing aerosols into the stratosphere potentially could provide a global cooling effect but would not address other issues such as ocean acidification. Climate intervention will not be discussed here further; rather, the focus of this section is on actions that directly involve the carbon cycle.

The study of MacDonald et al. (2016) estimated that U.S. carbon emissions from the power sector could be reduced by as much as 80% relative to 1990 use without significantly increasing energy costs and using existing technology. Although some studies have argued that a complete transition to decarbonized energy systems is feasible (Jacobson et al., 2015), other authors have pointed out that a transition to a low-carbon energy system is likely to be difficult and expensive without using a range of options (Clack et al., 2017), including some contribution from fossil fuels. This issue is complex, and full discussion of it is beyond the scope of this report.

For the CCS option, there are many unknowns about its implementation and permanence. A special example of CCS involves renewable energy, in this case bioenergy CCS (BECCS), where energy is derived from burning biomass, capturing and storing the resulting CO_2, and then re-growing the biomass. Although BECCS is appealing because it replaces fossil fuels *and* removes carbon from the atmosphere, there is only one experimental biomass plant of this type and its technology suffers from the same uncertainty as other CCS types (Anderson and Peters 2016; Fuss et al., 2014).

Estimates of the potential for negative emissions are in the range of 1.6 to 4.4 Pg C per year or 34 to 105 Pg C by 2100 (Griscom et al., 2017; Houghton and Nassikas 2018). Achieving the potential of negative emissions, however, has other constraints involving competition for land area, water availability, albedo changes, and nutrient limitations (Smith et al., 2015). Most negative emissions activities on land are useful either as a bridge to a low–carbon emissions energy system for developing and implementing CCS or for assistance with future removals of previously emitted CO_2, but effects are limited in implementing long-term solutions because forests and soils cannot accumulate carbon at high rates indefinitely. The most rapid rates of carbon removal occur in the first 50 to 100 years of forest growth. Soils generally are slow to accumulate carbon, although that process in forests may last for centuries if the forests remain undisturbed (Luyssaert et al., 2008). Thus, negative emissions are a part of the portfolio of mitigation activities, but the timing of impacts needs to be considered. These negative emissions cannot compensate for future emissions that either continue at current rates or increase (Gasser et al., 2015). Furthermore, the effects of climate change on the carbon balance of terrestrial ecosystems are uncertain, as suggested by the increased mortality of U.S. forests from droughts, insects, and fires.

Another unknown is how much of an overshoot is possible—that is, by how much and for how long emissions could exceed the limit imposed by a 2°C ceiling and their effects still be reversible. Moreover, questions include: How would they be reversed with only limited, available negative emissions? What are the tipping points? For example, warming already is thawing permafrost and thereby exposing long-frozen organic carbon to oxidation. Estimates

are that emissions of carbon from thawing permafrost could be 146 to 160 Pg C by 2100 (Schuur et al., 2015), enough to counter negative emissions. Similarly, disruption of tropical and subtropical ecosystems could lead to substantial releases of carbon into the atmosphere. Avoidance of tipping points is a paramount challenge to civilization. Only by continuing to seek a better understanding of the carbon cycle can the predictability of these events be improved.

SUPPORTING EVIDENCE

KEY FINDING 1

Atmospheric carbon dioxide (CO_2) has increased from a preindustrial abundance of 280 parts per million (ppm) of dry air to over 400 ppm in recent years—an increase of over 40%. As of July 2017, global average CO_2 was 406 ppm. Methane (CH_4) has increased from a preindustrial abundance of about 700 parts per billion (ppb) of dry air to more than 1,850 ppb as of 2017—an increase of over 160%. The current understanding of the sources and sinks of atmospheric carbon supports the dominant role of human activities, especially fossil fuel combustion, in the rapid rise of atmospheric carbon (*very high confidence*).

Description of evidence base

Preindustrial concentrations of CO_2, CH_4, and other trace species are known from measurements of air trapped in ice cores and firn from Greenland and Antarctica (e.g., MacFarling Meure et al., 2006). These measurements show that preindustrial levels of CO_2 and CH_4 were 280 ppm and 800 ppb, respectively. Contemporary global measurements of CO_2 and CH_4 are archived and documented at esrl.noaa.gov/gmd/ccgg/trends/global.html. Estimates of cumulative carbon emissions, along with atmospheric observations and estimates of net uptake by ocean or land, show that human emissions dominate the observed increase of CO_2 (Tans 2009). Analyses of "bottom-up" estimates of the CH_4 budget and atmospheric observations also support a strong role for anthropogenic emissions in the contemporary atmospheric CH_4 budget (Saunois et al., 2016).

Major uncertainties

There is a high degree of confidence in the overall increases in CO_2 and CH_4 since the preindustrial era. Attribution of these increases to anthropogenic emissions or natural emissions is subject to uncertainty (e.g., Saunois et al., 2016; Tans 2009). However, these uncertainties are unlikely to change the central conclusion that anthropogenic emissions have caused the significant increases in CO_2 and CH_4 since preindustrial times.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Observations clearly show substantial increases in greenhouse gas (GHG) concentrations since preindustrial times resulting from anthropogenic GHG emissions and land-use change.

Summary sentence or paragraph that integrates the above information

For Key Finding 1, there is very high confidence that CO_2 and CH_4 have increased by over 40% and 160%, respectively, since preindustrial times and that this increase is due to anthropogenic emissions. Uncertainties in natural exchanges among the atmosphere, ocean, and terrestrial biosphere and in anthropogenic emissions are unlikely to change the latter conclusion.

KEY FINDING 2

In 2011, the total global anthropogenic radiative forcing resulting from major anthropogenic greenhouse gases (not including anthropogenic aerosols) relative to the year 1750 was higher by 2.8 watts per meter squared (W/m^2). As of 2017, the National Oceanic and Atmospheric Administration's Annual Greenhouse Gas Index estimates anthropogenic radiative forcing at 3.1 W/m^2,

an increase of about 11% since 2011. In 2017, CO_2 accounted for 2.0 W/m^2 and CH_4 accounted for 0.5 W/m^2 of the rise since 1750. The global temperature increase in 2016 relative to the 1880 to 1920 average was over +1.25°C, although this warming was partially boosted by the 2015–2016 El Niño. Global temperature, excluding short-term variability, now exceeds +1°C relative to the 1880–1920 mean in response to this increased radiative forcing (Hansen et al., 2017; *very high confidence*).

Description of evidence base

Global anthropogenic radiative forcing was extensively reviewed in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) (Myhre et al., 2013). The change in radiative forcing since 2011 and the contributions from CO_2 and CH_4 are based on global observations of radiatively active trace species and computed using empirical expressions derived from atmospheric radiative transfer models. Details are available at esrl.noaa.gov/gmd/aggi/aggi.html. Changes in global average temperature over the last century are based on the Goddard Institute for Space Studies surface temperature analysis (GISTEMP, data.giss.nasa.gov/gistemp; Hansen et al., 2017).

Major uncertainties

The uncertainty of radiative forcing calculations is about 10% (Myhre et al., 2013), including uncertainty of the atmospheric radiative transfer model and the global abundance of trace species. Uncertainty of global average temperature trends is determined by the distribution, type, and length of surface observation sites. The effects of these factors are discussed extensively by Hartmann et al. (2013) and also by Hansen et al. (2010, 2017).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Observations and models clearly demonstrate that radiative forcing has increased substantially since preindustrial times and that this increase is ongoing, resulting primarily from the observed increase in atmospheric GHG concentrations.

Summary sentence or paragraph that integrates the above information

For Key Finding 2, there is very high confidence in the value of global anthropogenic radiative forcing (2.8 W/m^2) and the fact that CO_2 accounts for the largest share of anthropogenic forcing, with CH_4 accounting for half the remainder. There is very high confidence that this increased radiative forcing has led to global average temperature increases since the preindustrial era.

KEY FINDING 3

Global fossil fuel emissions of CO_2 increased at a rate of about 4% per year from 2000 to 2013, when the rate of increase declined to about 2% per year. In 2014, the growth in global fossil fuel emissions further declined to only 1% per year (Olivier et al., 2016). During 2014, the global economy grew by 3%, implying that global emissions became slightly more uncoupled from economic growth, likely a result of greater efficiency and more reliance on less carbon intensive natural gas and renewable energy sources. Emissions were flat in 2015 and 2016 but increased again in 2017 by an estimated 2.0% (*high confidence*).

Description of evidence base

Quantification of global fossil fuel emissions relies mainly on energy consumption data collected by multiple international organizations such as the International Energy Agency (IEA), the Carbon Dioxide Information Analysis Center (CDIAC), the United Nations (UN), and the Energy Information Administration (EIA). UN energy statistics are used to estimate the amount of CO_2 released by gas flaring, and production statistics are used to quantify emissions from cement production. More details on estimation of global fossil fuel emissions are given by Le Quéré et al. (2016) and Ciais et al. (2013).

Major uncertainties

Uncertainty of global fossil fuel emissions is approximately 5% when expressed as a standard deviation (Le Quéré et al., 2016). This assessment of uncertainties includes the amounts of fuel consumed, the carbon and heat contents of fuels, and the combustion efficiency. Although typically considered as constant in time, the uncertainty expressed as a percentage of total emissions is in reality growing in time, as a higher fraction of total emissions come from emerging economies and developing countries with less sophisticated accounting (Le Quéré et al., 2016; Marland et al., 2009). The majority of the uncertainty is likely to be in the form of systematic errors for individual countries, resulting from biases inherent to their energy statistics and accounting methods (Le Quéré et al., 2016).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Energy consumption data clearly show that global fossil fuel emissions have grown over the past decades, with only slight decreases in certain individual years.

Summary sentence or paragraph that integrates the above information

For Key Finding 3, there is high confidence that fossil fuel emissions increased at a rate of 4% per year, until recently when they began to slow even as the U.S. economy grew. The slowing of emissions occurred even as the global economy was growing, implying greater reliance on lower carbon–emitting energy sources.

KEY FINDING 4

Net CO_2 uptake by land and ocean removes about half of annually emitted CO_2 from the atmosphere, helping to keep concentrations much lower than would be expected if all emitted CO_2 remained in the atmosphere. The most recent estimates of net removal by the land, which accounts for inland water emissions of about 1 petagram of carbon (Pg C) per year, indicate that an average of 3.0 ± 0.8 Pg C per year were removed from the atmosphere between 2007 and 2016. Removal by the ocean for the same period was 2.4 ± 0.5 Pg C per year. Unlike CO_2, CH_4 has an atmospheric chemical sink that nearly balances total global emissions and gives it an atmospheric lifetime of about 9 to 10 years. The magnitude of future land and ocean carbon sinks is uncertain because the responses of the carbon cycle to future changes in climate are uncertain. The sinks may be increased by mitigation activities such as afforestation or improved cropping practices, or they may be decreased by natural and anthropogenic disturbances (*high confidence*).

Description of evidence base

Using observations of CO_2 accumulation in the atmosphere and statistics on fossil fuel and cement production, the total uptake of carbon by the terrestrial ecosystem and the ocean can be resolved as residual. Inland waters are implicitly included in the terrestrial component through this process. The partitioning of the residual uptake between land and ocean is more complicated and requires the use of upscaled quantities such as partial pressure of CO_2 (pCO_2) measurements in seawater or measurements of atmosphere-land biosphere fluxes to understand contemporary fluxes and their variability. Among these two major sinks, the oceanic sink generally is understood to be better constrained by independent observations. In terms of interannual variability, substantial uncertainty remains for both oceanic and terrestrial sinks. In terms of the cumulative sink, cumulative oceanic uptake is best constrained by interior data for the ocean (e.g., Khatiwala et al., 2009, 2013), while the cumulative land uptake typically is understood as the difference between cumulative emissions and the estimated cumulative oceanic sink. In addition to the more direct data-based constraints, models of oceanic circulation often are used with pCO_2 measurements to estimate oceanic fluxes, and inverse modeling techniques also are used to estimate carbon uptake by global land and ocean. Inverse modeling combines information from atmospheric observations, atmospheric transport models, and best-available estimates of carbon fluxes from land and ocean via models and observations. Recent synthesis studies by Le Quéré et al. (2016 and 2017) overview the recent carbon budget. Future uptake by land and ocean is estimated using models of the terrestrial and oceanic carbon cycle coupled to climate simulations (e.g., Friedlingstein et al., 2014).

Major uncertainties

The partitioning of carbon fluxes between land and ocean has significant uncertainty resulting from sparse observational coverage of atmospheric concentration and fluxes. Models of ocean-land carbon exchange must be evaluated against observations of carbon fluxes and storage in ecosystems, but in general there is not enough global coverage. Similarly, large regions that are important for understanding the global carbon budget, such as the tropics and Siberia, are not covered by atmospheric observations. This lack of observational coverage makes accurate estimates of the partition of carbon uptake between global land and ocean difficult to achieve using inverse modeling. Uncertainties in atmospheric transport models add to the problem of sparse observational coverage. Increased observational coverage offered by space-based instruments may improve the situation in the future, assuming technical limitations can be understood and overcome. The future evolution of the carbon cycle, including climate–carbon cycle feedbacks, is highly uncertain (e.g., Friedlingstein et al., 2014), and the use of inverse techniques to understand the carbon budget over recent decades could help to improve simulations of the future carbon budget. Future carbon cycle–climate feedbacks are expected to be positive (Ciais et al., 2013).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Observations and models clearly demonstrate that about half of annually emitted CO_2 is absorbed by the terrestrial biosphere and by oceans. However, the exact partitioning between the land and ocean sinks is somewhat uncertain, while projections of the future of this uptake are highly uncertain.

Summary sentence or paragraph that integrates the above information

For Key Finding 4, there is very high confidence that the land and ocean are absorbing a significant amount of carbon emitted by fossil fuel use. The partitioning of this uptake between the land and ocean is more uncertain. The future evolution of the global carbon cycle is also uncertain.

KEY FINDING 5

Estimates of the global average temperature response to emissions range from +0.7 to +2.4°C per 1,000 Pg C using an ensemble of climate models, temperature observations, and cumulative emissions (Gillett et al., 2013). The Intergovernmental Panel on Climate Change (IPCC 2013) estimated that to have a 67% chance of limiting the warming to less than 2°C since 1861 to 1880 will require cumulative emissions from all anthropogenic sources to stay below about 1,000 Pg C since that period, meaning that only 221 Pg C equivalent can be emitted from 2017 forward. Current annual global CO_2 emissions from fossil fuel combustion and cement production are 10.7 Pg C per year, so this limit could be reached in less than 20 years. This simple estimate, however, has many uncertainties and does not include carbon cycle–climate feedbacks (*medium confidence)*. These conclusions are consistent with the findings of the recent *Climate Science Special Report* (USGCRP 2017).

Description of evidence base

Cumulative carbon emissions are quantified for Key Finding 5 using energy consumption statistics as described for Key Finding 3. The cumulative emissions required for staying below 2°C are estimated using climate models.

Major uncertainties

There is a range of plausible responses of global temperature to carbon emissions as a result of uncertainty in climate models, especially modeling cloud, aerosol, and carbon cycle feedbacks. In particular, the range of climate model sensitivity to a doubling of CO_2 is 1.5 to 4.5°C, suggesting uncertainty in the amount of cumulative carbon emissions that cannot be exceeded to stay below a global temperature increase of no more than 2°C. In addition, some potential carbon cycle–climate feedbacks, such as the effect of carbon emissions from permafrost thaw, are highly uncertain and may significantly lower the cumulative amount of carbon that can be emitted before the 2°C global temperature increase limit is exceeded.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Based on climate models, temperature observations, and inventories of cumulative GHG emissions, it is clear these emissions have resulted in the observed global temperature increase. However, there remains some uncertainty about the exact temperature response to future emissions due to uncertainty about climate feedbacks.

Summary sentence or paragraph that integrates the above information

For Key Finding 5, carbon emissions would have to be slowed and reduced within a few decades to avoid a high probability of global temperature increases that exceed 2°C. Over half the cumulative emissions allowable for a 67% chance to stay below 2°C may already have been emitted, and current emissions rates suggest that emitting the remainder may take as little as 20 to 40 years. There is a medium degree of confidence in the remaining emissions available to keep temperature increases below a given level.

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2 The North American Carbon Budget

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KEY FINDINGS

1. North America—including its energy systems, land base, and coastal ocean—was a net source of carbon dioxide to the atmosphere from 2004 to 2013, contributing on average about 1,008 teragrams of carbon (Tg C) annually (±50%) (*very high confidence*).

2. Fossil fuel emissions were the largest carbon source from North America from 2004 to 2013, averaging 1,774 Tg C per year (±5.5%). Emissions during this time showed a decreasing trend of 23 Tg C per year, a notable shift from the increasing trend over the previous decade. The continental proportion of the global total fossil fuel emissions decreased from 24% in 2004 to 17% in 2013 (*very high confidence*).

3. Approximately 43% of the continent's total fossil fuel emissions from 2004 to 2013 were offset by natural carbon sinks on North American land and the adjacent coastal ocean (*medium confidence*).

4. Using bottom-up, inventory-based calculations, the *Second State of the Carbon Cycle Report* (SOCCR2) estimates that the average annual strength of the land-based carbon sink in North America was 606 Tg C per year (±75%) during the 2004 to 2013 time period, compared with the estimated 505 Tg C per year (±50%) in ca. 2003, as reported in the *First State of the Carbon Cycle Report* (CCSP 2007). There is apparent consistency in the two estimates, given their ranges of uncertainty, with SOCCR2 calculations including additional information on the continental carbon budget. However, large uncertainties remain in some components (*very high confidence*).

5. The magnitude of the continental carbon sink over the last decade is estimated at 699 Tg C per year (±12%) using a top-down approach and 606 Tg C per year (±75%) using a bottom-up approach, indicating an apparent agreement between the two estimates considering their uncertainty ranges.*

**Note: Confidence level excluded due to Key Finding's emphasis on methodological comparisons.*

2.1 Introduction

Since the Industrial Revolution, human activity has released into the atmosphere unprecedented amounts of carbon-containing greenhouse gases (GHGs), such as carbon dioxide (CO_2) and methane (CH_4), that have influenced the global carbon cycle. For the past three centuries, North America has been recognized as a net source of CO_2 emissions to the atmosphere (Houghton 1999, 2003; Houghton and Hackler 2000; Hurtt et al., 2002). Now there is greater interest in including in this picture emissions of CH_4 because it has 28 times the global warming potential of CO_2 over a 100-year time horizon (Myhre et al., 2013; NAS 2018).

The major continental sources of CO_2 and CH_4 are 1) fossil fuel emissions, 2) wildfire and other disturbances, and 3) land-use change. Globally, continental carbon sources are partially offset by sinks from natural and managed ecosystems via plant photosynthesis that converts CO_2 into biomass. The terrestrial carbon sink in North America is known to offset a substantial proportion of the continent's cumulative carbon sources. Although uncertain, quantitative estimates of this offset over the last two decades range from as low as 16% to as high as 52% (King et al., 2015). Highlighted in this chapter are persistent challenges in unravelling CH_4 dynamics across North America that arise from the need to fully quantify multiple sources and sinks, both natural (Warner et al., 2017) and anthropogenic (Hendrick et al., 2016; Turner et al., 2016a; NAS 2018). Adding to the challenge is disagreement on whether the reported magnitudes of CH_4 sources and sinks in the United States are underestimated (Bruhwiler et al., 2017; Miller et al., 2013; Turner et al., 2016a).

At the global scale, about 50% of annual anthropogenic carbon emissions are sequestered in marine

and terrestrial ecosystems (Le Quéré et al., 2016). Temporal patterns indicate that fossil carbon emissions have increased from 3.3 petagrams of carbon (Pg C) per year to almost 10 Pg C over the past 50 years (Le Quéré et al., 2015). However, considerable uncertainty remains in the spatial patterns of emissions at finer scales over which carbon management decisions are made. Most importantly, the sensitivity of terrestrial sources and sinks to variability and trends in the biophysical factors driving the carbon cycle is not understood well enough to provide good confidence in projections of the future performance of the North American carbon balance (Friedlingstein et al., 2006; McGuire et al., 2016; Tian et al., 2016).

2.1.1 Approaches for Estimating Carbon Budgets

Historically, the existence (if not the magnitude) of the land sink has been confirmed by inventory-based approaches involving the extrapolation of ground-based measurements to regional, national, and continental scales (Caspersen et al., 2000; Goodale et al., 2002; Pan et al., 2011). Regional- to continental-scale estimates of the magnitude and variability of the terrestrial carbon sink differ substantially among assessments, depending on the measurement or scaling approach used and the budget components considered (Hayes and Turner 2012; King et al., 2015). Estimations of land-based carbon budgets over large domains, typically involving a combination of measurements and modeling, generally can be categorized as either "top-down" (atmosphere-based) approaches or "bottom-up" (biosphere-based) approaches (e.g., field measurements and ecosystem process models).

Top-down approaches provide a reliable constraint on overall land-atmosphere carbon exchange based on direct measurement of spatial and temporal patterns in CO_2 concentrations. Regional-scale estimates of net ecosystem exchange (NEE; i.e., the net exchange of CO_2 between land and atmosphere) are derived from these observations using different techniques ranging from simple boundary-layer budget approaches (Wofsy et al., 1988) to upscaling eddy covariance data (Jung et al., 2009; Xiao et al., 2014) to more complex inverse modeling of atmospheric transport (Gurney et al., 2002). Atmosphere-based estimates are broadly inclusive and treat all surface-atmosphere CO_2 exchange as one integrated flux. However, such estimates have limited attribution information on 1) stock changes within individual components, 2) internal processes, 3) lateral transfers, or 4) the exact location of carbon sinks and sources, which is derived from biosphere-based approaches.

Plot-based measurements serve as the basis for bottom-up approaches—either directly, as input to inventory-based methods (e.g., Birdsey and Heath 1995; Stinson et al., 2011), or indirectly through their use in calibrating ecosystem process models (e.g., McGuire et al., 2001). Although researchers can apply bottom-up approaches at broad scales to estimate flux components individually, evidence suggests there are important carbon pools and fluxes that are undersampled, have large or unknown uncertainties, and are not inventoried or modeled (Hayes et al., 2012; Warner et al., 2017). Despite these limitations, bottom-up methods (e.g., inventories) typically are cited in broader-scale carbon cycle assessments (e.g., Goodale et al., 2002; Pacala et al., 2007; Pan et al., 2011) that favor these approaches for their use of large amounts of measurements, ability to track the total change in ecosystem carbon pools, and comparability among estimates.

2.1.2 Carbon Cycling Synthesis Efforts

Terrestrial carbon budget estimates at global, national, and continental scales have proliferated in recent years. Prominent examples are the Forest Inventory and Analysis (FIA) Program of the U.S. Forest Service (fia.fs.fed.us) within the U.S. Department of Agriculture (USDA), the National Aeronautics and Space Administration's (NASA) Carbon Monitoring System (carbon.nasa.gov), and the National Oceanic and Atmospheric Administration's (NOAA) CarbonTracker (esrl.noaa.gov/gmd/ccgg/carbontracker; see also Appendix C: Selected Carbon Cycle Research Observations and Measurement Programs, p. 821). The U.S. Forest Service is

adopting a new approach to carbon accounting that moves FIA data through time by attributing changes in the complete set of pools to disturbance and land use (Woodall et al., 2015). The goal of this new approach is to provide improved estimates of the magnitude and uncertainty of carbon fluxes, along with more detailed information on the drivers and fate of carbon change. In the last decade, the understanding of the North American carbon budget has moved beyond terrestrial emissions and sinks to incorporate anthropogenic, aquatic, and coastal margin CO_2 and CH_4 dynamics. Since the *First State of the Carbon Cycle Report* (SOCCR1; CCSP 2007), multiple research efforts have aimed to synthesize and reconcile estimates across the key components of the continental-scale carbon cycle. A series of studies borne from the REgional Carbon Cycle Assessment and Processes (RECCAP) initiative has provided diagnosis and attribution of carbon cycle dynamics for global regions, including North America (King et al., 2015). Designed to advance research from SOCCR1 toward the *Second State of the Carbon Cycle Report* (SOCCR2), several "interim synthesis" studies organized by the North American Carbon Program (NACP; nacarbon.org) compared observational, inventory-based, and modeled estimates of carbon stocks and fluxes across sites (Schwalm et al., 2010), within subregions (Schuh et al., 2013), and over the continent (Huntzinger et al., 2012). Currently, the Global Carbon Project (globalcarbonproject.org) develops global- and regional-scale estimates of CO_2 (Le Quéré et al., 2018) and CH_4 (Saunois et al., 2016) budgets. Collectively, these efforts comparing and synthesizing information across various sources of data and methods have improved the understanding of the North American carbon cycle.

2.1.3 Chapter Objectives

This chapter synthesizes the latest scientific information on the North American carbon budget, incorporating terrestrial, anthropogenic, aquatic, and coastal margin CO_2 and CH_4 dynamics. The estimates used to develop the continental-scale budget presented here are summarized from previous results based on different methodological approaches encompassing three countries (i.e., Canada, the United States, and Mexico), the U.S. National Climate Assessment regions, and the major carbon sectors (see Figure 2.1, p. 75). Specifically, this chapter follows the estimates of North American carbon stocks and fluxes synthesized and reported in Chapter 3 of SOCCR1 (Pacala et al., 2007). That analysis defined the reported estimates as "ca. 2003" to represent the approximate time period of SOCCR1. Here, these estimates are updated for the 2004 to 2013 time frame, or the decade since SOCCR1. However, SOCCR2 does not always rigidly follow these exact dates when combining and reconciling various reported estimates of the different components that make up the carbon budget. As explained where appropriate within this chapter, some datasets have a temporal resolution allowing precise time periods to be summarized, but others do not. As such, this chapter attempts to synthesize the various budget components using reported estimates and datasets generally representative of the 2004 to 2013 time period. Also summarized in this chapter are the historical and current context of continental carbon fluxes and stocks; recent findings of indicators, trends, and feedbacks; and a discussion about social drivers and implications for carbon management decisions.

2.2 Historical Context

2.2.1 Continental Net Carbon Source

A review of updated information and new studies since SOCCR1 (CCSP 2007) has established the current understanding of the North American carbon budget presented here. Previous studies have addressed the North American carbon budget for periods that preceded SOCCR1 (e.g., Goodale et al., 2002). Historically, North America is considered a net source of carbon, having contributed to the rise of global GHGs in Earth's atmosphere over the past century (Le Quéré et al., 2016). This continental carbon source is driven entirely by anthropogenic emissions, primarily via the combustion of fossil fuels to meet energy demands from the industrial and transportation sectors of the United States, Canada, and Mexico. Since the 1970s, total fossil

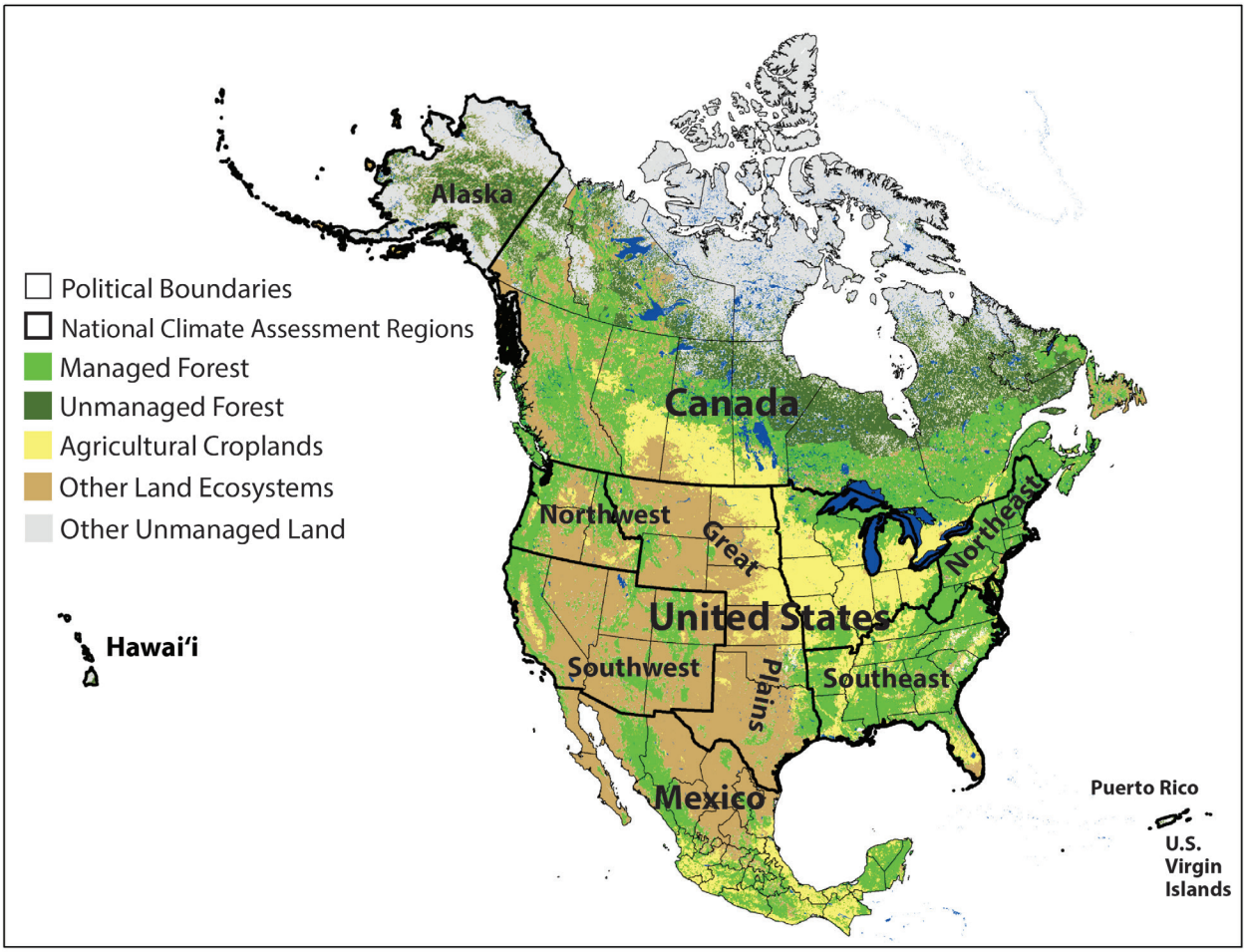

Figure 2.1. Spatial Domain of the Carbon Budget Synthesis for North America. Broadly represented in this map are the general carbon cycle sectors of forests, agriculture, other lands, and coastal regions intersected by the national boundaries of Canada, the United States, and Mexico. [Data source: Sector coverage is based on land-cover data developed by Wei et al. (2013) for the model-inventory comparison study of the North American Carbon Program regional interim synthesis.]

fuel emissions from these countries have increased approximately 1% per year according to the historical data reported in SOCCR1 (Pacala et al., 2007). In 2003, the three countries combined to emit approximately 1,900 teragrams of carbon (Tg C) per year, or about 27% of the global total according to fossil fuel inventory data at the time (Field et al., 2007). Of these three, the United States contributed 85% of that total. Although total U.S. emissions increased at a rate of about 1% per year for the 30 years leading up to 2003, the country's per capita emissions remained relatively constant, with its carbon intensity (i.e., emissions as a function of gross domestic product) decreasing by 2% over this time period. More recent analyses suggest a 2.8% decline in total North American emissions from 2003 to 2010, with 3.4% and 7.2% decreases in the United States and Canada, respectively, countered by a 13.6% increase in Mexico (King et al., 2012). From 1990 to 2009, North American fossil fuel emissions averaged an estimated 1,700 Tg C per year (Boden et al., 2015), or 25% of the global total during this two-decade period (King et al., 2015).

2.2.2 Continental Land and Coastal Ocean Sinks

North American land and its adjacent ocean almost certainly represent a net sink for atmospheric CO_2 excluding anthropogenic emissions (King et al., 2015; Peters et al., 2007). In the ca. 2003 time frame, which includes SOCCR1, North America's terrestrial carbon sink was estimated to be about 505 Tg C per year (±50%), representing about 15% to 40% of continental fossil fuel emissions at that time (Pacala et al., 2007). More recent analyses suggest that the terrestrial carbon sink continues to offset a substantial proportion of the carbon from fossil fuel emissions, though estimates of this proportion range from as low as 16% to as high as 52% over the last two decades (King et al., 2015). The potential North American CO_2 sinks vary from 327 to 931 Tg C per year, compensating for about 35% of the continent's fossil fuel CO_2 emissions (King et al., 2012). Natural and managed ecosystems in the United States and Canada consistently have been considered a sink (ranging from 200 to 700 Tg C per year and 44 to 238 Tg C per year, respectively; King et al., 2012). Inventory-based estimates of Mexico's carbon budget ca. 1990s suggest that the land was a source of approximately 24 to 48 Tg C per year due to emissions resulting from deforestation (Pacala et al., 2007; deJong et al., 2010). However, modeling studies—including both atmospheric inversions and terrestrial process-based approaches—have estimated Mexican ecosystems to be net sinks of about 9 to 31 Tg C per year attributed to the carbon uptake by vegetation exceeding other losses (King et al., 2012; Murray-Tortarolo et al., 2016). Overall, the North American land sector has the potential to take up an estimated 634 Tg C per year from the atmosphere, with an associated uncertainty of ±26% (King et al., 2012).

These estimates, based on combining carbon budget accounting across various sectors, attribute the sink primarily to forest growth, storage in wood products, and carbon sequestration in agricultural soils. For a more comprehensive estimate of the "apparent" sink (i.e., the total net absorption from the atmosphere), SOCCR1 expanded the inventory estimates to include the export of carbon outside the continental borders (Pacala et al., 2007). Accounting for these lateral transfers suggested a net export of carbon off the continent in the form of wood and agricultural products, as well as through river-to-ocean transport. Because these horizontal transfers are not vertical fluxes back to the atmosphere, adding them increased the estimated total North American atmospheric sink to 666 Tg C of the continent's annual emissions.

2.2.3 Carbon Estimates: Methods, Associated Uncertainties, and Research Gaps

Confidence in inventory-based estimates of the North American carbon budget varies by sector according to the coverage of observations and measurements associated with that sector. Relative to the estimates of other components of the continental carbon cycle, the magnitudes of annual fossil fuel emissions from energy and transportation inventories in Canada, the United States, and Mexico, as reported in SOCCR1, were well known and considered with 95% confidence to be within ±10% of the estimates (CCSP 2007). The estimates for the natural carbon sink components ca. 2003 were more uncertain, considered with 95% confidence to be within ±50% of the reported estimates (Pacala et al., 2007). Studies attempting to quantify the continental-scale carbon sink have been based on 1) synthesis approaches that combine national inventory data for managed forests and agricultural lands in the United States and Canada; 2) estimates of land cover and land-use change in Mexico; and 3) bottom-up, empirical estimates of the contribution of noninventoried components.

Carbon inventories of the national forest and agricultural sectors employ one of a few different, primarily empirical, approaches, each with various levels of uncertainty associated with the estimates. The "stock-change" approach used for U.S. forests is based on the difference between complete inventories at two points in time (Heath et al., 2011; Smith et al., 2010), thus capturing the total change in

ecosystem carbon (see Ch. 9: Forests, p. 365). Alternatively, Canada's national forest carbon inventory is based on the "gain-loss" method, which starts with a complete inventory that then is updated by modeling forward the components of change, such as growth, mortality, decomposition, and disturbance (Kurz et al., 2009; Stinson et al., 2011). Inventories of agricultural soils in the United States and Canada use empirical (West et al., 2010) and numerical (Environment Canada 2011) models to assess the impacts of management practices on soil organic carbon (SOC) stocks, with an uncertainty of approximately ±30% for the estimate (Hayes et al., 2012). In the United States and Canada, forest and agricultural inventory programs organize and report information on productivity, stock changes, and harvested products, but Mexico's forestland historically has not been systematically inventoried. Instead, the country's land estimates largely have been drawn from "bookkeeping" accounting studies (de Jong et al., 2010; Masera et al., 1997) of carbon stocks resulting from land-use change and national reports (INECC/SEMARNAT 2015). These estimates are considered to have higher uncertainty overall (±100%) because of a lack of systematic methodology and repeated inventories throughout time (Vargas et al., 2017), although a national forest inventory is now in place in Mexico and has provided new estimates in this report (see Ch. 9: Forests).

Some important contributions to continental-scale carbon stocks and fluxes have high uncertainties (or neglect an estimate altogether) for specific components and geographical regions because of the lack of standardized formal inventories or a comprehensive set of measurements across North America. Some of these factors, such as woody encroachment, arid lands, wetlands, and inland waters, have been considered to act as sinks. However, estimates of carbon stock changes in these components have relied on limited measurements or modeled data and thus are considered highly uncertain (essentially 100% of the estimated magnitude; Pacala et al., 2007). In particular, the mechanism whereby woody plants encroach into grasslands and other nonforested lands represents a potentially large flux of carbon, but also was the most uncertain component in the North American carbon budget from SOCCR1 (CCSP 2007). Measured and modeled CO_2 fluxes of nonforested, noninventoried regions, such as the tundra biome (McGuire et al., 2012) and water-limited ecosystems (Ahlstrom et al., 2015; Poulter et al., 2014), suggest that these fluxes are important budget components, but ascertaining whether they act as net sinks or sources over the longer term is difficult because of their larger interannual variability.

Some potentially significant carbon budget components were not included in SOCCR1 or other synthesis efforts (e.g., King et al., 2015) due to a lack of inventories or other information sufficient for continental-scale estimation. Arguably, the most important "missing components" are 1) a large but vulnerable reservoir of carbon in northern permafrost soils (Schuur et al., 2015); 2) a potentially weakening sink in unmanaged boreal forests of interior Alaska and northern Canada (Hayes et al., 2011); and 3) the uncertain role of tidal wetlands, estuaries, and the coastal ocean in the continental budget (Bauer et al., 2013; McLeod et al., 2011). Many carbon budget synthesis studies generally have based their estimates on inventories of total carbon stock change (Pacala et al., 2007) or specifically on surface-atmosphere fluxes of CO_2 (King et al., 2015). Also, historically missing from carbon budget studies is a comprehensive assessment of CH_4 fluxes. Although CH_4 is an important carbon-containing GHG, CH_4 budget synthesis efforts have been limited to a few global-scale, atmospheric-based estimates (Dlugokencky et al., 2011) or to specific ecosystems such as wetlands (Bloom et al., 2017). Only recently have there been reports of continental-scale estimates of CH_4 or other GHG fluxes, particularly from bottom-up estimates of budget components (Sheng et al., 2017; Tian et al., 2015).

Alternative scaling methods may account for some of these unknown components from the inventories, though they have their own information gaps and sources of uncertainty. Previous studies comparing atmospheric approaches based on inversion

modeling over North America have suggested a much stronger land-based CO_2 sink than bottom-up estimates at both regional (Hayes et al., 2011; Turner et al., 2011) and continental scales (Hayes et al., 2012; King et al., 2012; Pacala et al., 2001). For example, the NACP interim synthesis activity reported a continental terrestrial carbon sink of approximately 325 ± 77% Tg C per year, an estimate much lower than the mean atmospherically-based estimate of 931 ± 72% Tg C per year (Hayes et al., 2012). Biases in boundary conditions and transport in atmospheric inverse modeling (AIM) frameworks could have led to overestimates of the strength of the carbon sink over the mid- to high-latitude regions of North America (Göckede et al., 2010; Stephens et al., 2007). The bottom-up modeling approach, meanwhile, has exhibited an extremely large range of flux estimates as a consequence of variation in structural formulation and process representation across the ensemble of terrestrial biosphere models (TBMs), along with differences in the climate and land-use datasets used as model drivers (Huntzinger et al., 2012; Schwalm et al., 2010). Comparisons have suggested that a large contribution of the noninventoried "additional fluxes" would need to be added to the inventory-based sink estimates in SOCCR1 (Pacala et al., 2007) and the NACP synthesis (Hayes et al., 2012) to approach the magnitude suggested by the means of the AIM and TBM model ensembles (King et al., 2012). Reconciling the estimates across these various scaling approaches, King et al. (2012) concluded that the "best estimate" of the magnitude of the continental land CO_2 sink early in this century was 635 ± 26% Tg C per year, offsetting about 35% of fossil fuel emissions over that time period.

2.3 Current Understanding of Carbon Stocks and Fluxes

Current estimates of carbon stocks available from the sector-based chapters across SOCCR2 are compiled in Table 2.1, p. 79. These estimates total about 627 Pg C stored in North American terrestrial ecosystems, particularly soils or sediments, which contain about 93% of the total stock. Notably, the magnitude of many soil pools across ecosystems has not been measured or estimated (see Table 2.1), leading to an unknown uncertainty in the size of this pool (see Ch. 12: Soils, p. 469). Estimates of vegetation carbon stocks generally are more comprehensive and precise than soil stocks because vegetation biomass—particularly in forests—can be estimated with inventory measurements and remote-sensing methods (Masek et al., 2015). Relative to the organic carbon stored in long-term soil pools, vegetation stocks are of much smaller magnitude and are more transient as a function of their higher turnover rates. The largest SOC pool, thought to be stored in northern high-latitude soils (Tarnocai et al., 2007, 2009), is vulnerable to decomposition and release to the atmosphere as permafrost thaws due to climate warming (Schuur et al., 2015). In general, however, a reliable estimate of total stocks at the continental scale currently is not possible, given the lack of comprehensive and systematic inventories across all the major components of the carbon cycle. Instead, the SOCCR2 synthesis effort focuses on the stock changes, fluxes, and transfers of carbon among the major terrestrial and coastal pools and the atmosphere.

All of the land, water, and coastal ocean flux estimates compiled in the budget presented here are considered to be the best available approximations of each sector's NEE, as shown in Table 2.2, p. 80, where a negative value represents a removal (i.e., sink) from the atmosphere. There is very high confidence that the North American continent—including its energy systems, land base, and coastal ocean—was a net source of carbon to the atmosphere from 2004 to 2013, having contributed on average approximately 1,008 Tg C per year (see Table 2.2). Natural sinks within North American land ecosystems, waters, and coastal ocean areas accounted for about 766 Tg C per year in net uptake from 2004 to 2013, offsetting about 43% of the total fossil fuel emissions over that time period. The largest sink in this continental-scale budget is the estimated 260 Tg C per year associated with inland waters. This estimate represents the net effect of inland waters on surface-atmosphere CO_2 exchange, accounting for lateral fluxes, gas emissions, and

Table 2.1. Estimated Stocks of Major North American Carbon Pools ca. 2013[a]

Carbon Pools	Canada	United States	Mexico	North America
Forest Biomass[b]	18,591	19,675	1,995	40,261
Forest Soils[c]	31,395	31,454	4,900	67,749
Agricultural Soils[d]	5,500	13,000	2,115	20,615
Grassland Biomass[e]	ND[f]	1,362	ND	1,362
Grassland Soils[g]	ND	6,049	4,100	10,149
Tundra Biomass[h]	1,010	350	NA[f]	1,360
Permafrost Soils[i]	ND	ND	NA[f]	459,000
Terrestrial Wetland Biomass[j]	946	412	16	1,374
Terrestrial Wetland Soils[k]	46,354	20,188	764	67,306
Inland Waters Sediment	ND	ND	ND	ND
Tidal Wetland and Estuary Soils[l]	ND	ND	ND	1,886
Coastal Ocean Sediment	ND	ND	ND	ND
Total Biomass	**20,547**	**21,799**	**2,011**	**44,357**
Total Soils	**83,249**	**70,691**	**11,879**	**626,705**

Notes

a) Data, in teragrams of carbon (Tg C), are from the sector-based chapters of this report.

b) Includes above- and belowground biomass plus deadwood (Table 9.2, p. 368).

c) Includes litter plus soil (Table 9.2).

d) Canadian estimate (Table 12.4, p. 483); U.S estimate from Rapid Carbon Assessment (RaCA) project (Table 12.1,p. 479); Mexican grazing lands estimate (Table 12.3, p. 482).

e) Estimate for conterminous United States only (Table 10.2, p. 403).

f) ND = no data; NA = not applicable.

g) Conterminous U.S. estimate (Table 10.2); Mexican estimate for "Other Lands" (Table 12.2, p. 481).

h) Tundra vegetation biomass for Canada and Alaska (Table 11.2, p. 442).

i) North America contains about one-third of the total estimated 1,460 to 1,600 petagrams of carbon (Pg C) stock of circumpolar permafrost soils (to a 3-m depth; see Ch. 11: Arctic and Boreal Carbon, p. 428).

j) Calculated as 2% of the total carbon stock of nonforested wetlands with peatland and mineral soils (Table 13.1, p. 514).

k) Calculated as 98% of the total carbon stock of nonforested wetlands with peatland and mineral soils (Table 13.1).

l) The total estimated carbon stocks from tidal wetlands, estuaries, and seagrasses (see Ch. 15: Tidal Wetlands and Estuaries, p. 596.

sedimentation (see Ch. 14: Inland Waters, p. 568), but it is considered a highly uncertain value (i.e., >100% of the estimate). The United States has the largest estimated land-based sink (360 Tg C per year) among the three countries, with the majority of net uptake occurring in its forest sector (201 Tg C per year). The U.S. forest sector estimate is among the most well constrained of the land ecosystem fluxes, with the true value likely to be within 25% of the estimate. Estimated uptake by the North American coastal ocean, at 160 Tg C per year, represents the other significant sink in the budget, having a medium certainty (i.e., within 50% of the estimate; see Ch. 16: Coastal Ocean and Continental Shelves, p. 649). All the estimated fluxes from land and coastal ocean ecosystems, compiled across the key

Table 2.2. Estimated Average Annual Net Emissions or Uptake for North American Carbon Cycle Components, ca. 2004 to 2013

Carbon Source (+) or Sink (–)	Canada	United States	Mexico	North America
***Fossil Source* (+)**				
Fossil Fuel Emissions (Ch. 3)	**148**	**1,496**	**130**	**1,774**
***Nonfossil Sink* (–) *or Source* (+)**				
Forests (Ch. 9)	16	–201	–32	–217
Agricultural Soils[a]	–1	–14	ND[b]	–15
Grasslands (Ch. 10)[c]	–3	–13	–9	–25
Arctic and Boreal Carbon (Ch. 11)	–9	–5	NA[b]	–14
Terrestrial Wetlands (Ch. 13)[d]	–18	–34	–7	–58
Inland Waters (Ch. 14)	ND	–85	ND	–260
Tidal Wetlands and Estuaries (Ch. 15)	ND	–8	ND	–17
Coastal Ocean (Ch. 16)	ND	ND	ND	–160
Total	**–15**	**–360**	**–48**	**–766**
Net Carbon Source	**134**	**1136**	**82**	**1,008**

Estimates of carbon emissions (sources) or uptake (sinks) are given in teragrams of carbon (Tg C) per year. These estimates are generally consistent with those in Figure 2.3, p. 83, although some components are defined differently and estimates include inferred values. Because the estimates have different spatial domains, the North American total does not always equal the sum of the three individual country estimates. Mathematical rounding accounts for the difference between the estimated North American net carbon source in this table (1,008 Tg C per year) and the carbon added to the atmospheric pool over North America in Figure 2.3 (1,009 Tg C per year).

Notes

a) Average annual stock change in soil organic carbon in croplands, 2000–2009; based on inventory estimates by King et al. (2015).

b) ND = no data; NA = not applicable.

c) "Inventory Analysis" estimates (Table 10.1, p. 401).

d) The "Net Carbon Balance" of nonforested wetlands with peatland and mineral soils (Table 13.1, p. 514).

sectors of the continental carbon budget, are based largely on inventory approaches or other bottom-up methods described in other chapters of this report.

2.3.1 Fossil Fuel Emissions

According to recent data (Boden et al., 2015), the United States emitted approximately 1,400 Tg C from fossil fuel burning, cement production, and gas flaring during 2013—accounting for 15% of the global total that year. The United States still contributes 85% of the combined fossil fuel emissions from the three North American countries, but in 2013 the continental proportion of the global total dropped to 17% from the 27% reported for 2003 in SOCCR1 (CCSP 2007). The proportional emissions among the three nations to the continental total have remained relatively constant over the last 30 years (about 8%, 86%, and 6% for

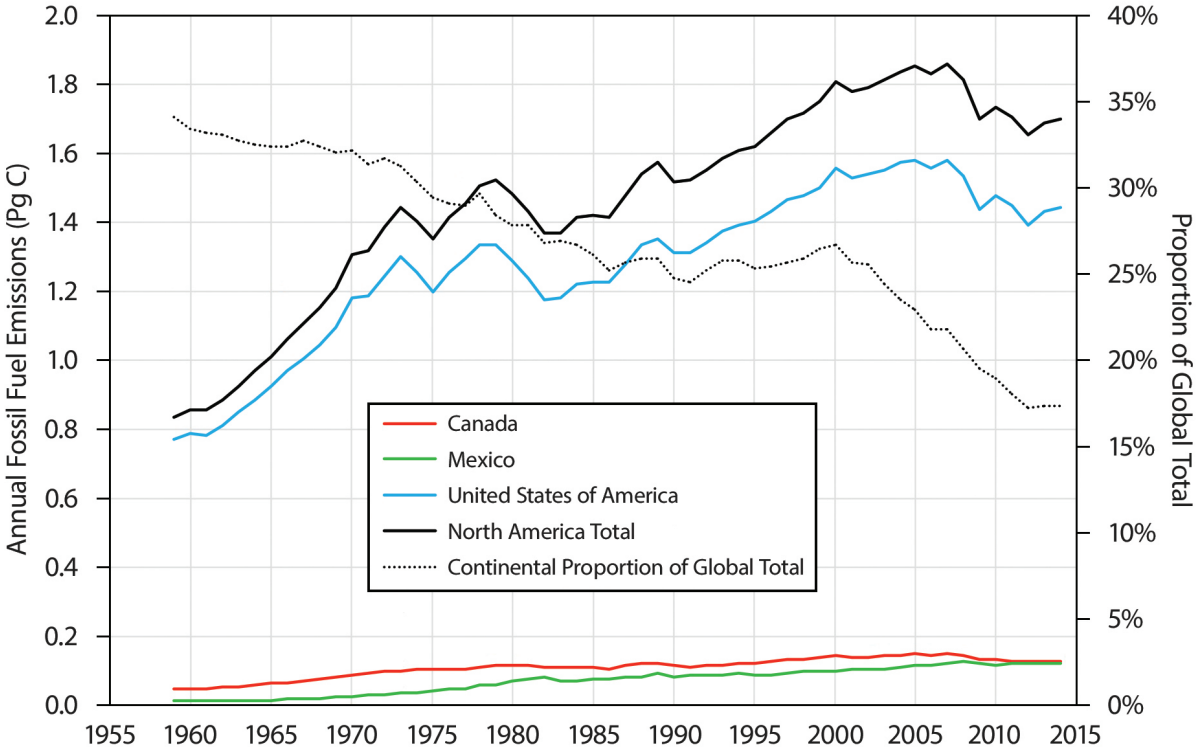

Figure 2.2. Annual North American Fossil Fuel Emissions from 1959 to 2014. Emissions values are given in petagrams of carbon (Pg C) for each country and for the continent as a whole (solid lines, left vertical axis). The dotted line shows the North American proportion of total global emissions (right vertical axis). [Data source: Carbon Dioxide Information Analysis Center (Boden et al., 2017).]

Canada, the United States, and Mexico, respectively), but the annual total magnitudes have varied in the last 10 years because of changing national and global socioeconomic factors (King et al., 2012). The annual rate of total fossil fuel emissions from North America indicates a notable change in trend during the decade since SOCCR1. Emissions from 1994 to 2003 showed a significant ($p<0.01$) increasing trend of 24 Tg C per year in contrast to a significant decreasing trend of 23 Tg C per year between 2004 and 2013 (see Figure 2.2, this page, and Ch. 8: Observations of Atmospheric Carbon Dioxide and Methane, p. 337). In 2007, the highest annual continental total fossil fuel emissions were recorded at about 1,800 Tg C. That level has not been exceeded since, with emissions estimates averaging about 1,700 Tg C per year from 2008 to 2013.

Among the various potential sources of emissions data (see Appendix E: Fossil Fuel Emissions Estimates for North America, p. 839), the Carbon Dioxide Information Analysis Center (CDIAC) dataset was chosen for its consistency and length of record (Boden et al., 2017). However, assigning an uncertainty to the CDIAC time series is a challenge. Andres et al. (2014) discuss various ways to characterize the uncertainty of this data product and suggest that a time-average uncertainty for the United States could be about 4% (or 2 standard deviations around the mean estimate). U.S. fossil fuel estimates reported in SOCCR1 used ±5% for the uncertainty of estimates for developed countries,

concordant with intercomparisons using the International Energy Agency dataset (IEA 2005). This chapter represents the uncertainty as the fractional range of estimates from five different inventories, averaged over time (see Appendix E, p. 839). By this measure, estimates of fossil fuel emissions have varied in uncertainty over time and among countries. The current ±5.5% uncertainty applies to the total estimated North American fossil fuel emissions of 1,774 Tg C per year from 2004 to 2013 as reported here (see Table 2.2, p. 80). The uncertainty around the mean estimate by country is highest for Canada (±30%) and lower for Mexico (±15%) and the United States (±6%). Precision of the fossil fuel emissions estimates is sensitive to the spatial and temporal scales of the inventories, and uncertainty at the scale of individual cities is poorly constrained, ranging from 50% to 100% variation around the mean (NAS 2010; Rayner et al., 2010; see also Ch. 4: Understanding Urban Carbon Fluxes, p. 189). Notably, current uncertainties associated with urban emissions typically exceed emissions reduction goals, making verification of these goals very challenging (Gurney et al., 2015; Hutyra et al., 2014).

2.3.2 Net Ecosystem Exchange

Calculating North American NEE involves assembling information from the major sectors (i.e., ecosystem compartments) for each country (see Table 2.2). The North American forest sector estimate (–217 Tg C per year) is based on current inventory estimates from this report (see Ch. 9: Forests, p. 365), including forestland NEE, the net of forest area gain and loss, the sink in urban trees, and emissions from biomass removal and use in each country (see Table 9.3, p. 371). The estimate for agricultural soils (–15 Tg C per year) is based on average annual stock change data for the 2000s, as compiled for the United States and Canada by King et al. (2015). Grassland estimates for the three countries (i.e., –3, –13, and –9 Tg C per year for Canada, the United States, and Mexico, respectively) represent average annual stock change in "other lands" between 2000 and 2006, as reported by Hayes et al. (2012; see also Table 10.1, p. 401). The estimated NEE for the Arctic-boreal region of North America (–14 Tg C per year) is based on a synthesis of eddy covariance flux data during the 2000s from research sites in Alaska and Canada (King et al., 2015; McGuire et al., 2012). Of this small sink, the portion attributed to the United States (–5 Tg C per year) is based on model simulations for upland ecosystems in Alaska (Genet et al., 2016) and, without a specific estimate for NEE, the remaining portion (–9 Tg C per year) is attributed to Arctic tundra and unmanaged boreal forest in Canada. The NEE estimate for terrestrial wetlands included in this budget (–58 Tg C per year) is based on information from Ch. 13: Terrestrial Wetlands, p. 507. However, only the contribution from nonforested wetlands (including both peatland and mineral soils) is included in the calculations (see Table 13.1, p. 514) because NEE from forested wetlands is considered to be accounted for already in the estimate for the forest sector. The estimated contribution to continental NEE from inland waters (–260 Tg C per year) is based on estimates from Ch. 14: Inland Waters, p. 568, and considered here to be the amount of carbon of terrestrial origin that is stored as sediment (155 Tg C per year) plus the amount exported to estuaries (105 Tg C per year; see Table 14.1, p. 576), as discussed in more detail below. The NEE estimate given for the combined tidal wetland and estuary ecosystems (–17 Tg C per year) is the balance of uptake by tidal wetlands (–27 Tg C per year) and outgassing by estuaries (10 Tg C per year), as estimated from information in Ch. 15: Tidal Wetlands and Estuaries, p. 596, and as discussed in more detail below. Finally, data from Ch. 16: Coastal Ocean and Continental Shelves, p. 649, are used to account for the uptake of atmospheric carbon by waters of the coastal ocean (–160 Tg C per year; see Table 16.5, p. 668) in the continental NEE budget estimates.

2.3.3 Stock Changes, Emissions, and Lateral Transfers of Carbon

Figure 2.3, p. 83, shows carbon flows among the major components of the North American carbon cycle for the decade since the ca. 2003 estimates

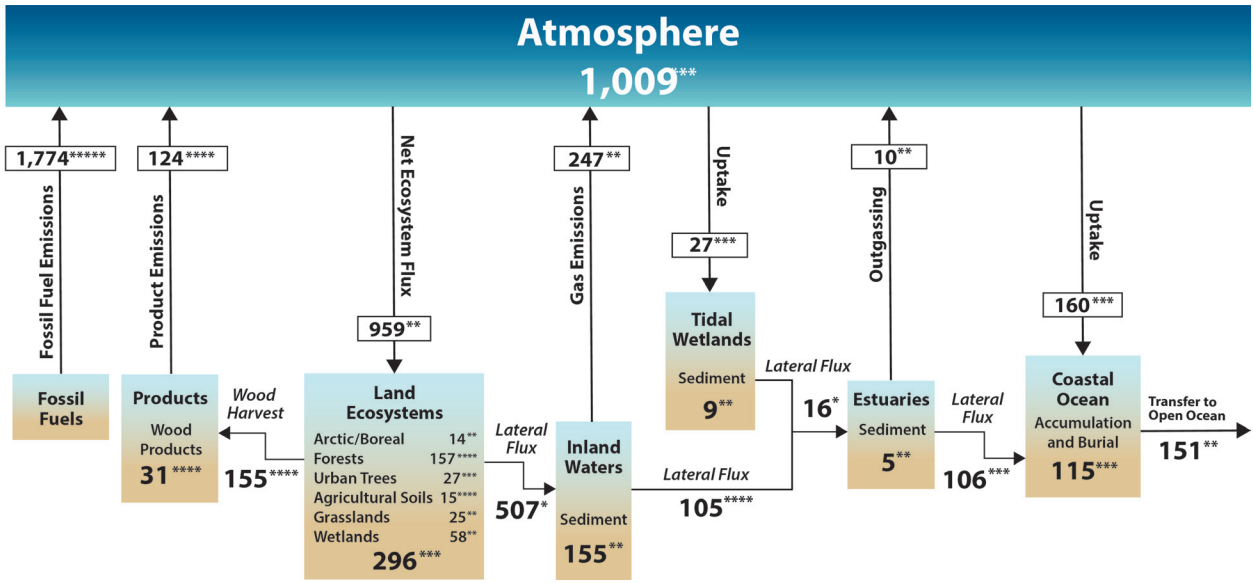

Figure 2.3. Major Components of the North American Carbon Cycle. For each component, estimates are shown for average annual stock changes (boxes), fluxes (vertical arrows), and lateral transfers (horizontal arrows) from ca. 2004 to 2013, the approximately 10-year period since the *First State of the Carbon Cycle Report* (CCSP 2007). All values are reported as teragrams of carbon (Tg C) per year. The sum of all fluxes between the atmosphere and the land or water components equals the increase in atmospheric carbon, so none of the lateral fluxes are counted as exchange with the atmosphere. Mathematical rounding accounts for the difference between this figure's estimated 1,009 Tg C per year added to the atmosphere over North America and the net carbon source estimate of 1,008 Tg C per year given in Table 2.2, p. 80. The net ecosystem flux of 959 Tg C per year from the atmosphere into land ecosystems is inferred from all the other fluxes based on the principle of conserving the overall mass balance of the different components. [Data sources: Data and certainty estimates are compiled and synthesized from the various chapters in this report. See Preface section titled "Treatment of Uncertainty in SOCCR2," p. 16, for an explanation of asterisks (i.e., certainty estimates).]

reported in SOCCR1. This figure aims to reconcile atmospheric flux and lateral transfer estimates with estimates of stock changes among the major sectors described throughout this report. Unlike estimates of sector-atmosphere exchange (i.e., NEE) in Table 2.2, p. 80, the boxes in Figure 2.3 represent the best estimates of stock change in each component, and the arrows represent the flows of carbon between components. As explained in Section 2.1, p. 72, the 2004 to 2013 time period chosen for this analysis generally represents the decade since the estimates reported in Chapter 3 of SOCCR1, which are given as ca. 2003. These exact dates are not used rigidly, however, when combining and reconciling various datasets in the budget synthesis reported here. Although some datasets—such as the fossil fuel emissions estimates (e.g., Boden et al., 2015)—have a temporal resolution allowing summary of precise time periods, other datasets, such as the periodically sampled forest inventory (see Ch. 9: Forests, p. 365), do not. As such, this chapter attempts to synthesize the various budget components using reported estimates and datasets generally representative of the 2004 to 2013 time period. While this coarser-than-annual level of precision does add an additional (but unknown) amount of uncertainty to the overall budget, this synthesis approach represents a best estimate of carbon stock changes and flows for an average year during the decade since the SOCCR1 synthesis.

Collectively, the land ecosystems of North America increased their carbon stocks at an estimated rate of about 296 Tg C per year over the ca. 2004 to 2013 time period, as shown in Figure 2.3, this page. The

majority (i.e., 53%) of this stock increase occurred in the managed forests of North America. The estimate for stock change in forests at the continental scale is the sum of the three countries, where stock change in forestland plus the net of forest area loss or gain was used to calculate U.S. and Canadian estimates and where forest NEE was used as an approximation of stock change in Mexico (see Table 9.3, p. 371). The stock change estimate for urban trees is distinguished from that of the forest sector, and the transfers and fluxes associated with the wood products pool are separated as well. Remaining land carbon gains occurred in smaller sinks associated with wetlands, urban trees in settled areas, grasslands, and agricultural soils, along with Arctic ecosystems and unmanaged boreal forests in Alaska and Canada. The stock change in each of these land ecosystems is approximated as their NEE estimates (see Table 2.2, p. 80). In addition to the net gain in land ecosystems, a substantial amount of carbon was transferred laterally out of land ecosystems into aquatic ecosystems (507 Tg C per year; see Table 14.1, p. 576) and pools of harvested products (155 Tg C per year; see Table 9.3, p. 371). The large amount of carbon estimated as lateral fluxes from land ecosystems originates in atmospheric CO_2 taken up by vegetation before being cycled through the soil pool and ultimately transported to aquatic systems. Similarly, the carbon in wood products also was taken up originally in forest trees before being removed in harvest. As such, the lateral transfer fluxes of carbon into both wood harvest and aquatic ecosystems are added to net stock change estimates to calculate an overall apparent net absorption of atmospheric CO_2 by North American land ecosystems (959 Tg C per year).

Net ecosystem flux into North American land ecosystems from the atmosphere is an estimated 959 Tg C per year (see Figure 2.3, p. 83). Of that amount, about 371 Tg C per year (or approximately 40%) is returned to the atmosphere through a combination of emissions from both inland waters (247 Tg C per year, which include emissions from rivers, streams, lakes, and reservoirs; see Table 14.1) and from woody biomass removal and use (124 Tg C per year; see Table 9.3). The rest of the lateral carbon transfers are stored as sediments in inland waters (155 Tg C per year; see Table 14.1), stored as wood in the products pool (31 Tg C per year; see Table 9.3), or exported to estuarine and coastal ocean systems (105 Tg C per year; see Table 14.1). Tidal wetlands are estimated to act as an additional small net sink of atmospheric CO_2 (27 Tg C per year) that either is stored in sediment (9 Tg C per year) or transferred laterally to estuaries (16 Tg C per year) that represent a small net outgassing of CO_2 (10 Tg C per year; see Ch. 15: Tidal Wetlands and Estuaries, p. 596). Coastal ocean areas are estimated to be a substantial net sink of carbon from the atmosphere (160 Tg C per year; see Table 16.5, p. 668) over the time period of analysis. Additional carbon is buried in estuary sediments (5 Tg C per year; see Ch. 15) and in the coastal ocean (115 Tg C per year; see Table 16.5). The remainder in the overall budget calculation represents a net export of carbon out of the continental system to the open ocean (151 Tg C per year; see Table 16.5).

Totaling all the vertical fluxes in Figure 2.3, p. 83, amounts to an overall estimate of 1,009 Tg C per year added to the atmosphere from North America when considering all sources and sinks over the 2004 to 2013 time period. (Note that Table 2.2, p. 80, provides a slightly different estimate of 1,008 Tg C per year due to rounding differences). In reconciling estimates of carbon stock change, fluxes, and lateral transfers across components in the overall budget, it is important to note that the total carbon from sedimentation, emissions, and export from inland waters (507 Tg C per year) represents carbon that has been taken up by terrestrial ecosystems and transferred laterally to inland waters. As such, this substantial amount of carbon is accounted for in the net ecosystem uptake estimate (959 Tg C per year) within the continental-scale, mass-balance budget (see Figure 2.3). Forest carbon budgets track the loss of carbon but may not distinguish between direct losses to the atmosphere and losses to streams and lakes, from which there are CO_2 emissions to the atmosphere. Thus, there is potential for an unknown amount of double-counting of CO_2 emissions assumed to be heterotrophic respiration

in forest ecosystem models and CO_2 emissions observed from inland water bodies and coastal margins. On the other hand, some of the CO_2 assumed lost from terrestrial ecosystems may in fact be accumulating in lake and ocean sediments.

2.3.4 Determining Coastal Ocean and Methane Impacts

The coastal margin sources and sinks within North America's carbon budget are not well understood, although land margin ecosystems provide a critical link in the lateral transport of carbon from land to ocean (Battin et al., 2009). This knowledge gap is largely due to limited information about the magnitude, spatial distribution, and temporal variability of carbon sources and sinks in coastal waters. Information from North America's estuaries indicates that they act as carbon sources and include 12% of global estuary emissions (Chen et al., 2013). The coastal ocean and continental shelf regions are estimated net sinks for carbon (Bourgeois et al., 2016; Laruelle et al., 2015), but upwelling regions can be "hotspots" of emissions during upwelling events (Reimer et al., 2013), resulting in current debate about the processes governing carbon dynamics in the coastal ocean (Cai 2011).

The potential benefits of the North American CO_2 sink (i.e., mitigating against the buildup of GHGs in the atmosphere) may be negated wholly by emissions of non-CO_2 GHGs such as CH_4 and nitrous oxide (N_2O; Tian et al., 2015, 2016). North America is a net source of CH_4 to the atmosphere, and isotopic approaches to partition global integrated measurements of $\delta^{13}C$-CH_4 confirm a large source from agriculture, wetlands, and fossil fuels (Dlugokencky et al., 2009; Kirschke et al., 2013). The Global Carbon Project (www.globalcarbonproject.org/methanebudget/) recently estimated global and regional CH_4 sources and sinks for the 2003 to 2012 time period using both bottom-up and top-down approaches (Saunois et al., 2016). For North America, inventory-based estimates of anthropogenic CH_4 sources (e.g., fossil fuels, agriculture, and biofuels) ranged from 38 to 49 Tg CH_4 per year, while modeling estimates of CH_4 emissions from wetlands ranged from 23 to 80 Tg CH_4 per year (see Figure 2.4, p. 86). Compared to these bottom-up estimates, the top-down CH_4 emissions estimates based on AIM approaches generally were lower for natural sources (17 to 52 Tg CH_4 per year) but similar for anthropogenic sources (25 to 61 Tg CH_4 per year). Methane sinks include the oxidation of CH_4 either from reactions with atmospheric hydroxyl radicals or from methanotrophy in upland soils, estimated for North America to be from 5 to 16 Tg CH_4 per year (Kirschke et al., 2013). Confidence in estimates of CH_4 emissions typically is low at all spatial scales (Brandt et al., 2014; Kirschke et al., 2013; Miller et al., 2013). Wetland emissions uncertainty is dominated by inaccuracies in location, extent, and seasonal dynamics of the CH_4-producing area (Desai et al., 2015), and anthropogenic emissions uncertainty is related to oil and gas production and distribution (Brandt et al., 2014; Frankenberg et al., 2016; McKain et al., 2015). Uncertainties from energy-related activities derive from knowing neither the actual extent and duration of gas flaring, nor the magnitude of leakage from pipelines, distribution systems, and other point sources. A recent example is the Aliso Canyon, California, gas leak that released about 97 gigagrams of CH_4 to the atmosphere (Conley et al., 2016). Although this gas leak was measured and monitored, it was undetected for a time. The number of other leaks that may have gone undetected or unmeasured, and for how long, is uncertain.

2.4 Trends in North American Carbon Cycling

Most published information on carbon cycling across North America is focused on the United States and Canada; thus, there is greater uncertainty about carbon dynamics for Mexico (Vargas et al., 2012). Data from SOCCR1 (CCSP 2007) suggested a large uncertainty in lands with woody encroachment and wetlands, so resolving whether these places acted as persistent carbon sources or sinks across North America was not possible at the time. SOCCR2 assessments suggest that the main uncertainties are in grasslands, wetlands, inland

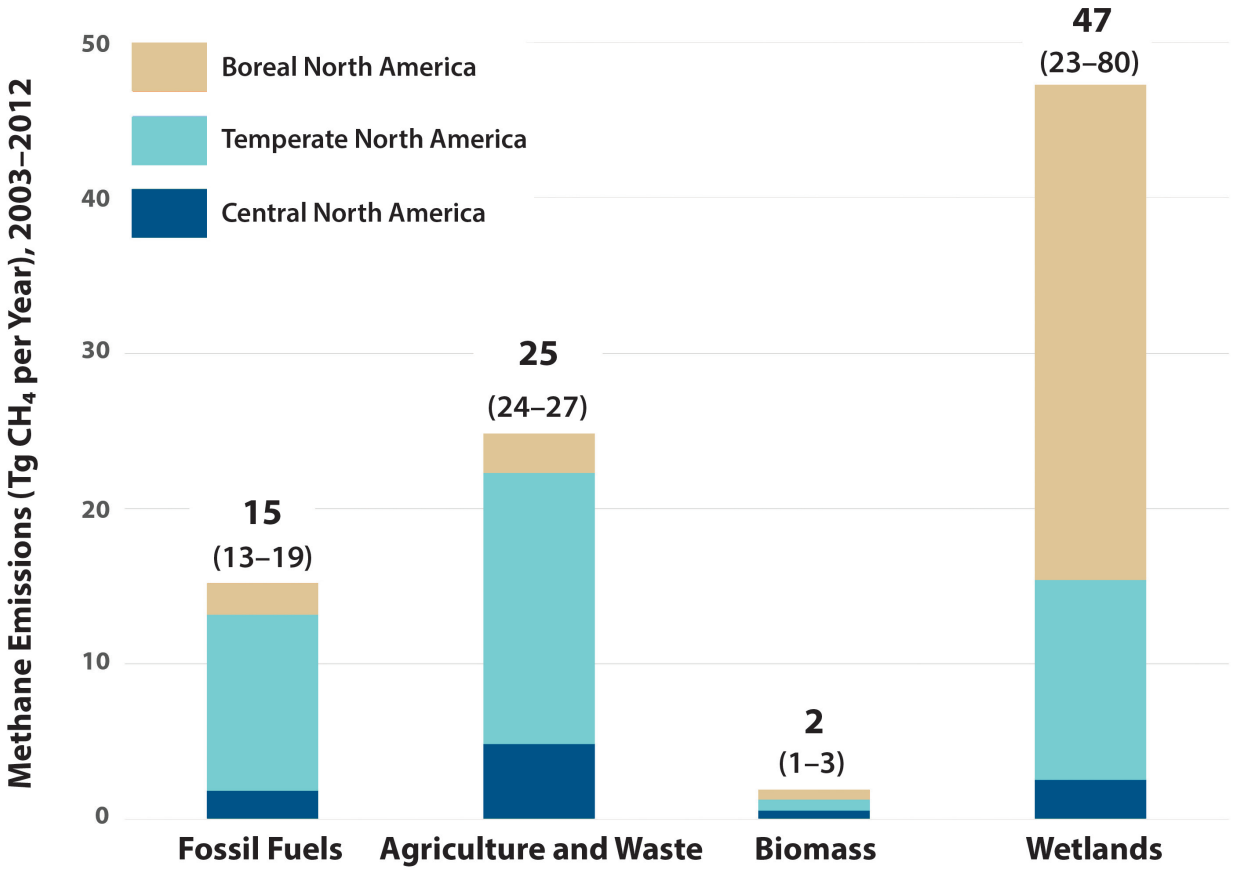

Figure 2.4. Sources of Methane (CH_4) Emissions Estimated from Bottom-Up Methods for Three Regions of North America from 2003 to 2012. The Boreal North America region includes Canada and Alaska; Temperate North America represents the conterminous United States; and Central North America includes Mexico, Guatemala, Belize, Honduras, El Salvador, Nicaragua, Costa Rica, Panama, and all islands and nations of the Caribbean and Antilles as categorized by Saunois et al. (2016). [Data source: North American CH_4 budget estimates, in teragrams (Tg) of CH_4 gas per year, compiled by Saunois et al., 2016.]

waters, and the Arctic. Importantly, because woody encroachment is considered implicitly in this report to be within grasslands and forests, it contributes to the uncertainty of these two sectors. Fossil fuel emissions continue to be the largest source of carbon to the atmosphere, and current estimates are consistent with those from SOCCR1. Attempts to quantify the coastal ocean component of the continental carbon budget has contributed a substantial amount of uncertainty in these assessments. Although SOCCR1 considered the coastal ocean a net source of carbon, new and better information from advances in measurement and modeling approaches now suggests it represents a net carbon uptake (see Ch. 16: Coastal Ocean and Continental Shelves, p. 649). The Arctic and boreal regions continue to be areas of uncertainty with large carbon stocks in permafrost and freshwater wetlands and with unknown land-atmosphere fluxes of CO_2 and CH_4 (McGuire et al., 2012; Petrescu et al., 2010; Schuur et al., 2015). Expanding research capabilities across different regions of North America will contribute to reducing uncertainty in key areas such as grasslands, wetlands, boreal and Arctic ecosystems, and tropical to subtropical regions.

For the ca. 2003 time frame, SOCCR1 estimated that about 30% of the combined fossil fuel emissions from the three North American countries were offset by CO_2 uptake in their ecosystems (Pacala et al., 2007). Based entirely on inventory estimates, carbon sinks in that analysis were attributed mostly to the forest sector, including tree growth, vegetation regeneration after agricultural land abandonment, fire suppression, and storage in wood products (Pacala et al., 2007). Estimates for fossil fuel emissions from 2000 to 2014 average approximately 1.8 ± 0.5 Pg C per year, with about 40% being offset by the land carbon sink (see Ch. 8: Observations of Atmospheric Carbon Dioxide and Methane, p. 337). Several studies support forests remaining as the key sector with a persistent sink globally (Pan et al., 2011) and across the United States (Woodall et al., 2015) and Canada (Kurz et al., 2013; Stinson et al., 2011). The SOCCR2 assessment presented here suggests that forests across North America offset fossil fuel emissions by about 12%, with U.S. forests accounting for most of that sink (i.e., 11%; see Table 2.2, p. 80). When these estimates are divided by fossil fuel emissions per country, the country-specific offset by forests suggests a slightly higher potential for Mexico (i.e., offsetting approximately 25% of in-country emissions), followed by the United States (about 13%). However, Canada's forests act as an additional source (about 11%) on top of the country's fossil fuel emissions. There is additional uncertainty surrounding boreal forests and tundra ecosystems in the northern high latitudes of North America (see Ch. 11: Arctic and Boreal Carbon, p. 428), particularly since these remote areas of unmanaged land in Canada and Alaska are not included in either of their country's formal carbon inventories and reporting programs (Kurz et al., 2009). In studies based on time series, optical satellite data have shown both "greening" in Arctic tundra and "browning" in boreal forests (e.g., Beck and Goetz 2011), suggesting regional variability in vegetation photosynthetic dynamics that could lead to carbon gains and losses, respectively (e.g., Epstein et al., 2012). Large carbon stocks stored in the frozen soils of North American landscapes underlain by permafrost are vulnerable to thaw under a warming climate, leading to carbon decomposition and subsequent release to the atmosphere as CO_2 or CH_4 (Hayes et al., 2014; Schuur et al., 2015). The increasing frequency and severity of disturbances in these regions, particularly wildfire, have the potential to impact vegetation and soil carbon stocks and fluxes in complicated feedback mechanisms (e.g., Abbott et al., 2016).

An analysis by King et al. (2015) demonstrates an 11% increase in the total magnitude of average annual continental emissions during 2000 to 2010 compared with 1990 to 2000. Since inventory data first became available in the 1960s, there has been a mostly uninterrupted increasing trend in overall fossil fuel emissions (Pacala et al., 2007). However, over the last decade, the combined fossil fuel emissions from Canada, the United States, and Mexico have been flat or declining. Combined annual emissions ranged from 1.7 to 1.8 Pg C between 2008 and 2013 and have not exceeded the approximately 1.9 Pg C peaks during 2005 and 2007 (see Figure 2.2, p. 81). The lower emissions total resulted from the 2007 to 2009 global economic recession and subsequent decline in energy consumption by the industrial and transportation sectors (see Ch. 3: Energy Systems, p. 110). From 2000 to 2009, annual per capita emissions were an estimated 20 tons (t) CO_2 in the United States, 18 t CO_2 in Canada, and 4 t CO_2 in Mexico. These estimates compare with a substantial decrease in per capita emissions by 2015 for the United States and Canada (about 17 t CO_2 and 16 t CO_2, respectively) and a stabilization in emissions for Mexico (about 4 t CO_2 per person; Le Quéré et al., 2016).

The trends in CH_4 emissions have been variable in recent decades, showing a renewed growth rate in global atmospheric concentrations since 2007 following a period of stabilization (Nisbet et al., 2016). However, the most recent budget by Saunois et al. (2016) compares CH_4 emissions from two decades: 2000 to 2009 and 2003 to 2012. This study found no significant increase in total natural and anthropogenic emissions for boreal North America

(20 Tg CH_4 per year) and central North America (11 Tg CH_4 per year), and even a slight decrease for the conterminous United States (from 43 to 41 Tg CH_4 per year). Although shortwave infrared measurements of CH_4 from the Greenhouse Gases Observing Satellite (GOSAT) indicate a 30% increase from 2002 to 2014 in central United States, the U.S. Environmental Protection Agency's (EPA) GHG inventory shows no such increase in anthropogenic emissions, despite a 20% increase in oil and gas production (Turner et al., 2016a). Changes in CH_4 emissions from high-latitude regions thus far appear to be fairly insensitive to warming (Sweeney et al., 2016), suggesting that changes in agriculture and livestock management are the key drivers in the recent increase in global CH_4 emissions (Schaefer et al., 2016). Using a one-box isotopic model, Schaefer et al. (2016) suggest that, outside the Arctic, activities related to food production are most likely responsible for the increasing CH_4 concentration in the atmosphere since 2007. Some research also considered a decrease in the hydroxyl sink for CH_4 as a driver of the renewed growth rate (Rigby et al., 2008); however, more recent multitracer assessments do not support this theory (Nisbet et al., 2016).

Monitoring networks suggest that the coastal margins of North America currently act as a net CO_2 sink, where the net uptake of CO_2 from the atmosphere is driven by high-latitude regions; however, the net flux from coastal margins is not well constrained (see Figure 2.4, p. 86, and Ch. 16: Coastal Ocean and Continental Shelves, p. 649). Ocean acidification trends are difficult to identify in coastal waters because highly variable carbonate chemistry is influenced by seawater temperature and transport, primary production, respiration, and inputs from land, in addition to the uptake of anthropogenic CO_2 from the atmosphere. In coastal ocean areas, major concerns for marine organisms, particularly calcifiers, are the increasing partial pressure of CO_2 (pCO_2) in seawater and reductions in pH that reflect greater acidity associated with increasing dissolved CO_2 concentrations in equilibrium with rising atmospheric CO_2—processes that could trigger ecosystem-scale effects. Ocean acidification also affects commercial shellfish stocks (mainly in the northwestern United States) and other environmental services (e.g., coastal protection by reefs) that ultimately may affect the carbon storage capacity of coastal ocean areas (see Ch. 17: Biogeochemical Effects of Rising Atmospheric Carbon Dioxide, p. 690).

SOCCR2 assessments provide high confidence that human activities (e.g., urban emissions, land management, and land-use change) will continue to be important drivers of carbon cycle changes across North America into the future. Current land use and land-use change result in net CO_2 emissions for Canada and Mexico, but future land use and land-use management potentially could result in net carbon sequestration (e.g., 661 to 1,090 Tg of CO_2 equivalent[1] by 2030; see Ch. 19: Future of the North American Carbon Cycle, p. 760). However, there are large uncertainties in predicting future land-use trajectories. In addition, fossil fuel emissions from the energy sector may continue to be a large source of carbon, but future projections are uncertain because of changes in technologies (see Ch. 1: Overview of the Global Carbon Cycle, p. 42, and Ch. 3: Energy Systems, p. 110) and efforts to reduce fossil fuel emissions. By 2040, estimates project that North American fossil fuel emissions will range from 1.6 to 1.9 Pg C per year, representing either a 9% decrease or a 6% increase in absolute emissions compared to 2015 levels (see Ch. 19, p. 760).

2.5 Regional Context

2.5.1 Canada, the United States, and Mexico

Efforts to understand the North American carbon cycle—including its stock and flux changes and socioecological implications—cross sociopolitical and economic boundaries. This report shows that regional efforts have measured, modeled, and scaled carbon sources and sinks across North America and quantified the uncertainties associated with those

[1] Carbon dioxide equivalent (CO_2e): Amount of CO_2 that would produce the same effect on the radiative balance of Earth's climate system as another greenhouse gas, such as methane (CH_4) or nitrous oxide (N_2O), on a 100-year timescale. For comparison to units of carbon, each kg CO_2e is equivalent to 0.273 kg C (0.273 = 1/3.67). See Preface for details.

estimates. Arguably, the most carbon cycle information is available for the United States, followed by Canada and Mexico. This information availability translates into higher confidence for estimates of carbon dynamics across the conterminous United States and Canada but lower confidence for Mexican estimates.

In general, SOCCR1 and subsequent publications (see sections above) suggest that terrestrial ecosystems in Mexico act as net sources of carbon to the atmosphere (due to land use and agricultural practices), while those in the United States and Canada tend to be net sinks of carbon from the atmosphere. In contrast, the United States is the highest emitter of fossil fuel emissions, followed by Canada and Mexico. These dynamics are related to differences in socioecological drivers that regulate carbon dynamics among the three countries, influencing the continental-scale carbon cycle.

The United States is characterized by a stable forestland, whose area gains and losses have roughly balanced over the last century (see Ch. 9: Forests, p. 365), enhancing the terrestrial carbon sink. In contrast, the large U.S. economy and population have high energy demands that contribute to the largest carbon emissions in North America. U.S. fossil fuel emissions were 1.5 Pg C per year (±6%) from 2004 to 2013 (see Table 2.2, p. 80), or approximately 4,700 kilograms (kg) C per person. Canada is characterized by an extensive natural resource base, where forests represent the largest ecosystem carbon pool. These forests have high disturbance rates and low productivity, resulting in an overall nearly neutral carbon balance. Although Canada's per capita emissions rate of 4,100 kg C is similar to the U.S. rate, its lower population resulted in substantially smaller fossil fuel emissions (148 Tg C per year ± 2%) from 2004 to 2013. In contrast, Mexico is characterized by higher-productivity forests (particularly its tropical forests), but also by more frequent natural disturbances (e.g., droughts, hurricanes, and fires) and high pressure on the use of natural resources that drives land-use change. Mexico contributed 130 Tg C per year (±15%) in fossil fuel emissions from 2004 to 2013, and its per capita emissions rate (1,000 kg C) is much lower than that of the United States and Canada because of its relatively large population with lower energy consumption.

Fully understanding differences in carbon dynamics across North America requires identifying the size of its carbon pools and the influence of climate feedbacks (e.g., changes in temperature or precipitation patterns) on the capacity of the pools to sequester or release carbon. In addition, differences in population migration patterns (e.g., changes between rural and urban populations), along with economic energy demands, determine anthropogenic drivers and feedback mechanisms of carbon exchange across the three countries of North America.

2.5.2 National Climate Assessment Regions of the United States

Terrestrial ecosystems in the eastern United States—located roughly within the Northeast, Midwest, Southeast, and Caribbean National Climate Assessment regions—together have acted as a substantial carbon sink in recent decades (Xiao et al., 2014; Zhu and Reed 2014), largely because of carbon accumulation in forests recovering from past disturbances (Williams et al., 2012). Most of the carbon sink in the eastern United States is in the Northeast and Southeast regions; the carbon sink in the Midwest region is relatively small in comparison. This regional difference is influenced mainly by the dominance of forests in the Northeast and Southeast regions and of agricultural lands in the Midwest. Projected carbon uptake in the Northeast and Southeast regions between 2006 and 2050 is expected to decrease from the current level, primarily because of forest aging in these regions (Liu et al., 2014). A better understanding of forest carbon dynamics is needed to quantify the impacts of 1) forest management, including the locations and intensity of widespread partial cutting in the Northeast region (Zhou et al., 2013); 2) disturbances such as windstorms (Dahal et al., 2014); 3) climate and atmospheric changes including CO_2 fertilization (Norby and Zak 2011); and 4) wildland fires

(Turetsky et al., 2014). Forest land uses including harvesting (i.e., clear-cutting and partial cutting, with forests remaining as forests) and conversion to other land uses are important driving forces of carbon cycling, not only for direct immediate carbon removal from these activities, but also for subsequent activity-dependent paths of changes in carbon storage. Although wildland fires have contributed only a small source effect on the total U.S. net carbon balance in recent decades (Chen et al., 2017), the area burned by wildland fires and the associated GHG emissions are projected to increase in the future (Hawbaker and Zhu 2014). Carbon stored in the Atlantic coastal wetlands is particularly vulnerable to wildland fires because of land-use activities (Flores et al., 2011).

Terrestrial ecosystems in the Great Plains region acted as a carbon sink from 2001 to 2005 (Zhu et al., 2011). Their current rate of uptake is expected to remain steady or decrease slightly until 2050 as a result of climate change and projected increases in land use. Methane emissions from wetlands and N_2O emissions from agricultural lands are high for the region and expected to increase. The amount of area burned in the Great Plains and the region's GHG emissions are highly variable, both spatially and temporally. Although estimates for the amount of area burned are not expected to increase substantially over time, fire-resultant GHG emissions are expected to increase slightly for a range of climate projections. Land-use and land-cover changes are major drivers of shifts in the region's carbon storage. Consequently, future carbon storage in the Great Plains region will be driven largely by the demand for agricultural commodities, including biofuels, which might result in substantial expansion of agricultural land at the expense of grasslands, shrublands, and forests. Converting these areas to agricultural lands, among other land-use changes, may lead to considerable loss of carbon stocks from Great Plains ecosystems. Moreover, studies have not fully examined the important regional effects of climate variability and change, such as droughts, floods, and fluctuations in temperature and moisture availability.

The western United States, consisting roughly of the Northwest and Southwest climate regions, acted as a net terrestrial carbon sink from 2001 to 2005 (Zhu and Reed 2012). The carbon density in these regions demonstrated high spatial variability in relation to variation along a climate gradient from the Marine West Coast to Warm Desert ecoregions. Furthermore, drought is recognizably important in the interannual variability of carbon dynamics in water-limited ecosystems across the southwestern United States (Schwalm et al., 2012; Biederment et al., 2016). Compared to the region's contemporary rate of uptake, future carbon sinks in the western United States are projected to decline, mainly in ecosystems of the Northwest region in response to future climate warming and associated drought effects (Liu et al., 2012). Influenced by both climate and land-use changes, wildland fires have been major ecosystem disturbances in the Northwest and Southwest regions (Hawbaker and Zhu 2012), resulting in considerable interannual and regional variability in GHG emissions, mostly in the semiarid and arid Western Cordillera and Cold Desert ecoregions. From 2001 to 2005, average annual GHG emissions from the fires equaled 11.6% of the estimated average rate of carbon uptake by terrestrial ecosystems in the western United States. Under future climates scenarios, areas burned by wildland fires and the associated GHG emissions are projected to increase substantially from the levels of 2001 to 2005. Other ecosystem disturbances, such as climate- and insect-caused forest mortalities, are important drivers of carbon cycling in these regions, but incorporating these processes into regional carbon cycle assessments remains a major challenge (Adams et al., 2013; Anderegg et al., 2013; Hartmann et al., 2015).

Although forestlands of southeastern Alaska are included in national GHG reports, other regions of Alaska are not because field data for them is insufficient to support a formal inventory program and many areas are classified as "unmanaged" according to the Intergovernmental Panel on Climate Change. However, Alaska's high-latitude ecosystems are potentially more vulnerable to future climate change than regions

in the temperate zone because increasing temperatures may expose the substantial stores of carbon in the region to loss from increasing wildfire and permafrost thaw. To better understand these potential effects, researchers conducted a more comprehensive assessment of carbon stocks and fluxes of CO_2 and CH_4 across all ecosystems in Alaska by combining field observations and modeling (McGuire et al., 2016). The assessment found that temperate forests in southeastern Alaska store approximately 1,600 Tg C across the major pools, with about twice as much in live and dead tree biomass (1,000 Tg C) than in the SOC pool (540 Tg C). In contrast, the vast majority of carbon stocks in Alaska's northern boreal forest and Arctic tundra ecosystems occur in SOC (31 to 72 Pg C), much of which is stored in frozen ground (see Ch. 11: Arctic and Boreal Carbon, p. 428). Despite the average annual source of 5.1 Tg C from the boreal region due to wildfire, Alaskan upland ecosystems overall were estimated to be, on average, a net sink of 5 Tg C per year over recent decades (1950 to 2009). During the same period, this sink was offset partially by the state's wetland ecosystems that acted as a net source of 1.3 Tg C per year, including 0.93 Tg C per year in biogenic CH_4 emissions since 2000. Finally, the total net flux from inland waters across Alaska is estimated at approximately 41.2 ± 20 Tg C per year, where total net flux equals coastal export plus CO_2 emissions from rivers and lakes minus burial in lake sediments. However, projections from the Alaska assessment indicate that increased uptake in upland and wetland ecosystems over this century will more than compensate for sources resulting from wildfire, permafrost thaw, and wetland emissions. Carbon sinks in Alaska's upland and wetland ecosystems are projected to increase substantially (18.2 to 34.4 Tg C per year) from 2010 to 2099, primarily because of a 12% to 30% increase in net primary production associated with responses to rising atmospheric CO_2, increased nitrogen cycling, and longer growing seasons.

2.6 Societal Drivers, Impacts, and Carbon Management

Changes from local to global carbon dynamics in natural and anthropogenic systems have imminent consequences for humans because carbon is embedded in almost all social activities (see Ch. 6: Social Science Perspectives on Carbon, p. 264). The resultant social reliance on carbon by North American societies causes dependence on ecological, economical, and technological networks and systems that have carbon embedded in them (e.g., forestry, energy generation, transportation, fisheries, and agriculture). Thus, management decisions have to consider social drivers if the goal is to transition to low-carbon systems and make a substantial impact on the carbon cycle.

Social lifestyles and cultural backgrounds have been constrained historically by available resources, energy sources, and costs that have influenced the North American carbon cycle. For example, the proportional share of total continental fossil fuel emissions differs among the three North American countries (i.e., Canada, 11.9%; Mexico, 6.5%; and the United States, 81.6%); together these countries contribute 20% of global energy-related emissions (see Ch. 3: Energy Systems, p. 110). Urban development has resulted in spatially concentrated sources of energy demand and consequently high anthropogenic carbon emissions (see Ch. 4: Understanding Urban Carbon Fluxes, p. 189). Although the area of agricultural land for North America has remained constant in the last decade, regional carbon dynamics can be influenced by trends in food production and agricultural management (see Ch. 5: Agriculture, p. 229). Differences between cultural backgrounds and current policies are evident in tribal lands. Ideologies, local practices, government land tenure, and agricultural and water policies create challenges for defining carbon management practices (see Ch. 7: Tribal Lands, p. 303). Despite socioeconomic differences across North America, increasing demand for easily available energy has implications for the continental carbon cycle.

Regional carbon management decisions to mitigate CO_2 emissions could benefit from sector-specific accounting, focusing efforts on reducing atmospheric GHG concentrations and identifying options for carbon sinks. Compiled from the

chapters in this report, Table 18.1, p. 737, summarizes a set of management activities and their relative contributions to potential reductions in GHG emissions across the various sectors of the North American carbon budget. For example, North American forests have significant potential as a carbon sink, so mitigation options for this sector could use a systems approach to assess large uncertainties in future land use and predict subsequent impacts on forests (see Ch. 17: Biogeochemical Effects of Rising Atmospheric Carbon Dioxide, p. 690). These assessments will require quantifying changes in emissions associated with 1) forest ecosystems (e.g., changes in rates of land-use change), 2) harvested wood products and their substitution by high-emission products (e.g., steel and concrete), and 3) fossil fuels through the use of wood products (Kurz et al., 2016; Lemprière et al., 2013). The potential for changes to the carbon balance in the forest sector also will depend on societal drivers related to increases in urbanization and reduction of forested lands via land-use change. These processes could result in a loss of forest industrial capacity across North America that ultimately will limit the potential carbon sink of the forest sector. Therefore, socioecological factors could influence changes in emissions from different sectors, potentially requiring alternative practices to maintain the productivity of sector products (e.g., long-lived forest products) and ecosystems (i.e., carbon sequestration potential in long-term pools such as SOC).

Since SOCCR1, North American observational networks related to the carbon cycle (e.g., CO_2 and CH_4 stocks and fluxes from aquatic and terrestrial ecosystems) have increased (see Appendix C: Selected Carbon Cycle Research Observations and Measurement Programs, p. 821). Thus, carbon management decisions could benefit from a high degree of interoperability among government, research, and civil sectors within the countries and across North America. Interoperability in this context is defined as an organized collective effort needed to foster development and implementation of carbon management decisions and actions. Furthermore, interoperability has the ultimate goal to maximize sharing and use of information by removing conceptual, technological, organizational, and cultural barriers (Vargas et al., 2017). For example, interoperability could be increased by defining inventory protocols (i.e., a conceptual barrier), using standardized instrumentation (i.e., a technological barrier), defining the specific roles of participants (e.g., researchers and governmental agencies), and being sensitive to cultural expectations (e.g., perception of data ownership). Although sector- and country-specific barriers exist, moving toward a high degree of interoperability will facilitate anticipation, recognition, and adaptation of management decisions to make a positive impact on the continental carbon cycle.

2.7 Synthesis, Knowledge Gaps, and Outlook

SOCCR1 (CCSP 2007) concluded that North America was a net source of carbon to the atmosphere ca. 2003, with the magnitude of fossil fuel emissions outpacing the rate of carbon uptake by land sinks. The synthesis of carbon flux estimates in SOCCR2 suggests that North America has remained a carbon source in the decade since SOCCR1, continuing to contribute to the global rise in atmospheric CO_2 and CH_4 concentrations from 2004 to 2013. Synthesizing across the major continental-scale budget components, SOCCR2 assessments suggest that approximately 57% of the total fossil fuel emissions from Canada, the United States, and Mexico remains in the atmosphere after the offsetting portion is taken up by a net sink across North American land ecosystems, inland waters, and adjacent coastal ocean areas. This overall estimate of the "airborne fraction" of fossil fuel emissions is less than the estimated 70% reported in SOCCR1, a decrease that is a function of both a reduction in the total emissions estimate coupled with an increase in the net continental sink estimate for 2004 to 2013. The values in SOCCR2 also reflect additional information and improved understanding of components and sectors influencing the continental carbon budget, but large uncertainties in some components must be addressed to achieve a better understanding of the trends.

This report estimates that the total fossil fuel carbon source in North America from 2004 to 2013 was 1.8 Pg C per year, representing an approximately 5% reduction in annual emissions compared to the ca. 2003 estimate of 1.9 Pg C per year. The lower current emissions estimate is likely a result of changing technology, policy, and market factors (see Ch. 3: Energy Systems, p. 110). Despite the modest reduction in emissions, the fossil fuel source still represents the largest single component in the continental-scale carbon budget. The relative contributions from each of the three countries have remained constant since SOCCR1, with the United States continuing to contribute the vast majority (85%) of total continental emissions. The total fossil fuel emissions from energy and transportation systems across North America likely will remain the dominant source category and continue to outpace the ability of the continental land ecosystems, inland waters, and adjacent coastal ocean areas to take up this carbon in the future.

North America's natural and managed land ecosystems, inland waters, and adjacent coastal ocean areas likely will remain a net carbon sink, thereby partially constraining the airborne fraction of fossil fuel emissions and further mitigating climate impacts from rising atmospheric CO_2. Bottom-up, inventory-based analyses have confirmed the existence of the continental carbon sink, but the uncertainty associated with these approaches provides less confidence in estimates of the sink's magnitude than in the better-constrained estimates of fossil fuel emissions. The "best estimate" of the continental sink from 2004 to 2013 in SOCCR2 is 766 Tg C per year, compared to 505 Tg C per year estimated in SOCCR1. The difference in these two bottom-up estimates can be explained by the additional components considered in SOCCR2 that were not accounted for in SOCCR1. These components include Arctic and boreal ecosystems; estuaries; and updated information and accounting for grasslands, inland water fluxes, terrestrial and tidal wetlands, and the coastal ocean. Still, both the SOCCR1 and SOCCR2 estimates fall within the uncertainty bounds of the other and thus are not considered a trend nor significantly different from each other.

Given the large uncertainty in the bottom-up analysis, comparing it with top-down estimates is important to collectively provide an additional constraint on the overall continental sink estimate. Previous comparisons typically have shown mean estimates of the continental CO_2 sink from top-down atmospheric models to be much greater than those from bottom-up inventory and biosphere models, although within the large range of uncertainty in these estimates (King et al., 2012; Pacala et al., 2001). In a progression of studies over time, mean land sink estimates based on atmospheric models have decreased from 1,700 ± 500 Tg C per year (Fan et al., 1998) to 890 ± 409 Tg C per year (King et al., 2015). Meanwhile, best estimates for the sum of sink components from inventory-based methods will increase as additional components are included in the calculation. For example, including estimates of highly uncertain components (e.g., woody encroachment, wetlands, and the net flux in inland waters) increased the sink estimate to 564 Tg C per year from the 325 Tg C per year that only considered reported inventory estimates for forests and agriculture (Hayes et al., 2012). In conclusion, the larger bottom-up sink estimates approach the lower end of the uncertainty in the atmospheric model estimates as these additional components are added, though they also greatly increase the uncertainty of the estimates (King et al., 2012).

SOCCR2 shows further convergence between the top-down, continental-scale carbon sink estimate from atmospheric modeling and the synthesis of estimates from bottom-up approaches across the major components of North America (see Figure 2.5, p. 94). This convergence partly results from a series of operational, conceptual, and technological improvements. The analysis of a growing network of atmospheric measurements of CO_2 and CH_4 using inverse modeling techniques has increased significantly since SOCCR1. Several flux modeling systems produce regular continental-scale estimates on an operational basis, and regional

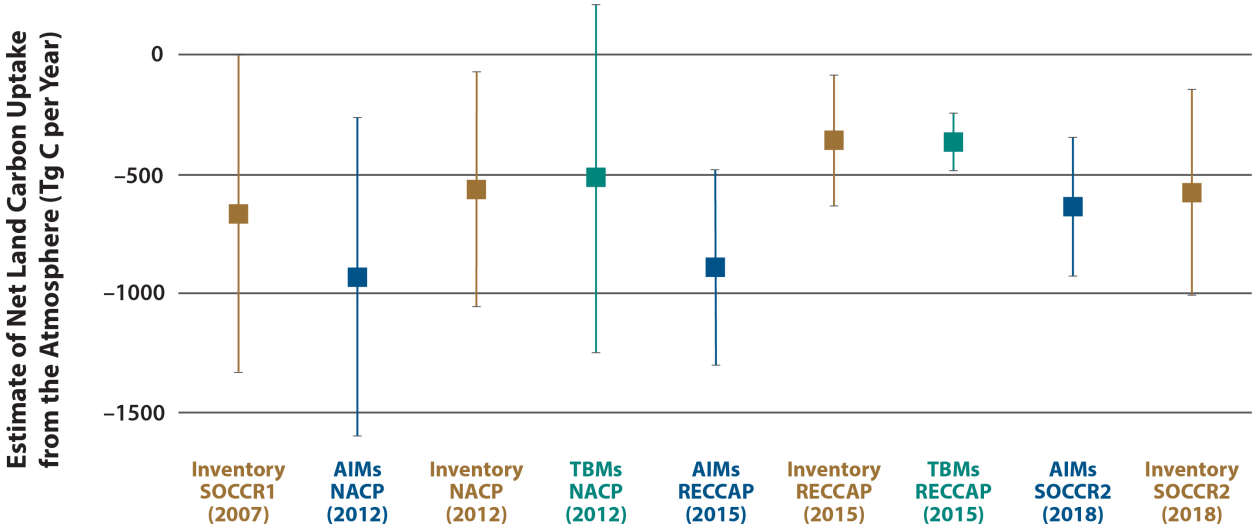

Figure 2.5. Estimates of the North American Carbon Sink in this Century. These estimates, in teragrams of carbon (Tg C) per year, are derived from inventory analysis, atmospheric inversion models (AIMs), and terrestrial biosphere models (TBMs). [Data sources: *First State of the Carbon Cycle Report* (SOCCR1; CCSP 2007), North American Carbon Program (NACP; Hayes et al., 2012), REgional Carbon Cycle Assessment and Processes (RECCAP) initative (King et al., 2015), and this report (SOCCR2). Publication year of each estimate is given in parenthesis.]

inverse modeling studies are now focused on specific land areas and individual megacities (see Ch. 8: Observations of Atmospheric Carbon Dioxide and Methane, p. 337). Furthermore, recent atmospheric inverse model analyses estimate the continental land sink to be 699 ± 82 Tg C per year, which includes all continental carbon fluxes from land and water but not the coastal ocean sink (see Ch. 8). These estimates are only slightly higher than the bottom-up estimate of 606 Tg C per year that is calculated by removing the coastal ocean sink from the continental total (see Table 2.2, p. 80). Considering the uncertainty ranges of the two approaches, there is an apparent agreement in the magnitude of the continental carbon sink over the last decade between the top-down and bottom-up estimates in this report. The inverse model analysis of atmospheric CO_2 data suggests that there is substantial variability in land-atmosphere carbon fluxes over North America from year to year, though a comparable analysis reported from bottom-up estimates is not possible here because of averaged stock change estimates over the longer time periods between inventories. Additionally, the atmospheric estimates show at least moderate evidence of an increasing rate of carbon uptake in the continental land sink from 2000 to 2014, but any such trend is difficult to ascertain from the bottom-up estimates between SOCCR1 and SOCCR2 because of differences in the components that are included and how they are calculated.

Given the general convergence with the current atmosphere-based estimates, the bottom-up estimates synthesized in this report are unlikely to be missing any major source or sink components in the budget (see Table 2.2, p. 80). Similar to the continental sink estimates reported in SOCCR1, the forest sector is among the largest sinks (217 Tg C per year), along with smaller but persistent sinks in agricultural soils (15 Tg C per year) and terrestrial wetlands (58 Tg C per year) in SOCCR2. To reiterate, additional small-sink components for Arctic and boreal ecosystems (14 Tg C per year) and tidal wetlands and estuaries (17 Tg C per year) in this report were not considered in SOCCR1. The most significant components now included in SOCCR2 are the net uptakes by inland waters (260 Tg C per

year) and by coastal ocean areas (160 Tg C per year). However, a large sink component associated with woody encroachment (120 Tg C per year) was included in SOCCR1 but is not explicitly separated in SOCCR2 because this potential sink mechanism is considered to be included within the forest and grassland estimates. The flux estimates from inland waters, the coastal ocean, and woody encroachment remain highly uncertain and should be prioritized for further study, given their potentially large contribution to the continental carbon budget.

Confidence in estimates of the overall, continental-scale carbon budget is expected to increase in the near future with more observations, improved data, and better understanding of the processes. More accurate, consistent, and highly resolved estimates among the various budget components likely will be helpful in informing management-scale decisions (see Ch. 18: Carbon Cycle Science in Support of Decision Making, p. 728). Though atmospheric measurements provide an integrated constraint on the overall budget and can detect variability and trends over short time frames, they currently offer limited attribution capability with respect to the various individual components. Bottom-up measurements and inventory estimates are needed to make projections for specific sectors and at the finer spatial scales at which the sectors are managed. These inventories, however, are often expensive and difficult to undertake. Moreover, they do not always obtain all the required measurements with consistent precision and, in many cases, cannot resolve key trends in sources and sinks or attribute their causes. Results from terrestrial biosphere model simulations offer the potential for process-based attribution of regional-scale carbon cycle dynamics (Turner et al., 2016b), but variability in response across the ensemble of model results leads to uncertainty in the predictions (Huntzinger et al., 2012, 2017). The move toward more regional-scale and sector-targeted atmospheric analyses should offer substantial help with these efforts, but advancements in bottom-up biosphere modeling frameworks will be necessary to improve confidence in future projections of the North American carbon budget (see Ch. 19: Future of the North American Carbon Cycle, p. 760). These estimates also will continue to benefit from the increasing availability of remote-sensing data provided by multiple platforms (Goetz and Dubayah 2014; Masek et al., 2015; Williams et al., 2014). Although there is value in retaining independence among the various top-down and bottom-up approaches for estimating and comparing carbon fluxes, the most significant progress likely will be made by increasing the formal integration of these approaches in future assessment and prediction frameworks that are more comprehensive and consistent.

SUPPORTING EVIDENCE

KEY FINDING 1

North America—including its energy systems, land base, and coastal ocean—was a net source of carbon dioxide to the atmosphere from 2004 to 2013, contributing on average about 1,008 teragrams of carbon (Tg C) annually (±50%) (*very high confidence*).

Description of evidence base

Key Finding 1 is supported by fossil fuel emissions data (Boden et al., 2015), forest inventories in the United States (Woodall et al., 2015; see Ch. 9: Forests, p. 365) and Canada (Stinson et al., 2011), atmospheric inverse modeling ensembles (see Ch. 6: Social Science Perspectives on Carbon, p. 264), terrestrial biosphere model ensembles (Huntzinger et al., 2012), synthesis studies from previous work (Hayes et al., 2012; King et al., 2012, 2015), and a compilation of estimates across the various chapters of this report.

Major uncertainties

Regional- to continental-scale estimates of the magnitude and variability of the terrestrial carbon sink differ substantially among assessments, depending on the measurement or scaling approach used and the budget components considered (Hayes and Turner 2012; King et al., 2015).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is very high confidence that the North American continent is a net source of carbon to the atmosphere given the convergence of evidence across multiple inventory, scaling, and modeling approaches. This evidence suggests that current levels of fossil fuel emissions far outpace the ability of terrestrial ecosystems to take up and store that carbon.

Estimated likelihood of impact or consequence, including short description of basis of estimate

The carbon source from North America very likely contributed to the global rise of carbon dioxide (CO_2) concentrations in the atmosphere from 2004 to 2013.

Summary sentence or paragraph that integrates the above information

The North American continent is very likely a net source of carbon to the atmosphere. Key Finding 1 is supported by the convergence in evidence across multiple inventory, scaling, and modeling approaches. The finding is corroborated by several other continental-scale synthesis studies from the *First State of the Carbon Cycle Report* (SOCCR1; CCSP 2007), the North American Carbon Program (e.g., Hayes et al., 2012), and the REgional Carbon Cycle Assessment and Processes (RECCAP; King et al., 2015). While the estimated source from fossil fuel emissions is relatively well constrained (within ±1%), the key uncertainty is the magnitude of the sink in land ecosystems, inland waters, and adjacent coastal ocean areas. The larger uncertainty of the sink estimate is reflected in differences in the results between inventory and modeling approaches, stemming primarily from measurement gaps in the inventories and many uncertain processes in model representations of ecosystems.

KEY FINDING 2

Fossil fuel emissions were the largest carbon source from North America from 2004 to 2013, averaging 1,774 Tg C per year (±5.5%). Emissions during this time showed a decreasing trend of 23 Tg C per year, a notable shift from the increasing trend over the previous decade. The continental proportion of the global total fossil fuel emissions decreased from 24% in 2004 to 17% in 2013 (*very high confidence*).

Description of evidence base

Key Finding 2 is supported by fossil fuel inventories collected by the Carbon Dioxide Information and Analysis Center (CDIAC) and made available in the territorial fossil fuel carbon emissions dataset (Boden et al., 2017). Among the various sources of emissions data (see Appendix E: Fossil Fuel Emissions Estimates for North America, p. 839), the CDIAC dataset was chosen for its consistency and length of record. However, to represent the data uncertainty, the SOCCR2 assessment used the fractional range of estimates from five different inventories, averaged over time.

Major uncertainties

The absolute values of greenhouse gas (GHG) emissions levels from energy consumption and production vary significantly due to differences in system definitions, inclusion of industrial process emissions, emissions factors applied, and other issues (see Ch. 3: Energy Systems, p. 110). Accuracy of the fossil fuel emissions estimates is less certain at finer spatial and temporal scales, and uncertainty at the scale of individual cities is not well constrained (Gurney et al., 2015; Hutyra et al., 2014; Rayner et al., 2010). Furthermore, the magnitude of methane (CH_4) leakage from fossil fuel production and use has a high degree of uncertainty in the inventories (Brandt et al., 2014).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is very high confidence that fossil fuel emissions are the dominant source of carbon from the North American continent.

Estimated likelihood of impact or consequence, including short description of basis of estimate

Fossil fuel emissions from North America very likely will continue to contribute substantially to the rise in global atmospheric CO_2 concentration.

Summary sentence or paragraph that integrates the above information

Total fossil fuel emissions from the Canadian, U.S., and Mexican energy and transportation systems very likely are and will continue to be substantially greater in magnitude than any other source category, including agriculture and livestock, land-use change, and natural disturbance.

KEY FINDING 3

Approximately 43% of the continent's total fossil fuel emissions from 2004 to 2013 were offset by natural carbon sinks on North American land and the adjacent coastal ocean (*medium confidence*).

Description of evidence base

Key Finding 3 is supported by fossil fuel emissions data (Boden et al., 2015), forest inventories in the United States (Woodall et al., 2015; see Ch. 9: Forests, p. 365) and Canada (Stinson et al., 2011), atmospheric inverse modeling ensembles (see Ch. 8: Observations of Atmospheric Carbon Dioxide and Methane, p. 337), terrestrial biosphere model ensembles (Huntzinger et al., 2012), and synthesis studies (Hayes et al., 2012; King et al., 2012, 2015).

Major uncertainties

The land sink is uncertain due to a lack of measurement precision in inventories, along with gaps in spatial coverage and uncertainty in specific components such as the soil carbon pool. The overall land sink is inferred from reconciling a number of estimates from different components, themselves often highly uncertain. In particular, the component with the largest estimate of the inferred ecosystem flux—the lateral transfer to the aquatic system—is also one of the least certain (see Table 2.2, p. 80).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

At least some portion of anthropogenic carbon emissions to the atmosphere is very likely offset by vegetation uptake and storage in North American land ecosystems. There is medium confidence in the "best estimate" of 43% as the proportion of total fossil fuel emissions taken up by North American land and coastal ocean areas.

Estimated likelihood of impact or consequence, including short description of basis of estimate

The natural ecosystems of the North American continent likely have represented a net carbon sink over the recent decade, thereby constraining the airborne fraction of anthropogenic emissions from fossil fuel carbon consumption and thus mitigating further climate impacts from rising atmospheric CO_2.

Summary sentence or paragraph that integrates the above information

For Key Finding 3, North America's natural and managed ecosystems and its adjacent coastal ocean likely will continue to take up some of the total fossil fuel carbon emitted to the atmosphere from anthropogenic activities. However, the fraction of emissions taken up by the ecosystem in the future is uncertain and will depend on energy use, the response of natural ecosystems to climate change and other disturbances, and human management of the land and the coastal ocean.

KEY FINDING 4

Using bottom-up, inventory-based calculations, the *Second State of the Carbon Cycle Report* (SOCCR2) estimates that the average annual strength of the land-based carbon sink in North America was 606 Tg C per year (±75%) during the 2004 to 2013 time period, compared with the estimated 505 Tg C per year (±50%) in ca. 2003, as reported in the *First State of the Carbon Cycle Report* (CCSP 2007). There is apparent consistency in the two estimates, given their ranges of uncertainty, with SOCCR2 calculations including additional information on the continental carbon budget. However, large uncertainties remain in some components (*very high confidence*).

Description of evidence base

Key Finding 4 is supported by observational evidence from forest inventories in the United States (Woodall et al., 2015) and Canada (Stinson et al., 2011), atmospheric inverse modeling ensembles (see Ch. 8: Observations of Atmospheric Carbon Dioxide and Methane, p. 337), terrestrial biosphere model ensembles (Huntzinger et al., 2012), and synthesis studies (Hayes et al., 2012; King et al., 2012, 2015). The U.S. forest sink is maintained because of the net accretion of forest land use in combination with continued forest growth (i.e., forests remaining forests; Woodall et al., 2015, 2016).

Major uncertainties

Components of the North American carbon cycle measured as part of formal inventory programs, such as the forest and agricultural sectors, are estimated with a high level of certainty. However, other components potentially contribute significantly to the magnitude of the continental carbon sink (see Table 2.2, p. 80). The largest of these comprises the net emissions from inland waters, which at the continental scale are poorly constrained (i.e., uncertainty is effectively 100% of the estimate). Also contributing substantially to the overall uncertainty are other important components of the land base in regions where measurement gaps exist over large areas, such as in Mexico and the remote northern areas of Canada and Alaska.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is very high confidence that the North American land base has maintained an overall carbon sink over the past decade, with net carbon uptake and storage in the vegetation and soils of natural and managed ecosystems.

Estimated likelihood of impact or consequence, including short description of basis of estimate

North America's natural ecosystems likely have maintained a net carbon sink over recent decades, thereby constraining the airborne fraction of fossil fuel carbon and mitigating further climate impacts from rising atmospheric CO_2.

Summary sentence or paragraph that integrates the above information

For Key Finding 4, the sink is likely to maintain its approximate current magnitude because of carbon uptake and storage in the forest sector (i.e., the land base and wood products).

KEY FINDING 5

The magnitude of the continental carbon sink over the last decade is estimated at 699 Tg C per year (±12%) using a top-down approach and 606 Tg C per year (±75%) using a bottom-up approach, indicating an apparent agreement between the two estimates considering their uncertainty ranges.

Description of evidence base

The integrated, continental-scale estimates of the overall carbon sink comprise compilations from 1) recent top-down, atmospheric approaches (see Ch. 8: Observations of Atmospheric Carbon Dioxide and Methane, p. 337); 2) comparisons of bottom-up, inventory-, and model-based estimates from the various sector-focused chapters in this report; and 3) data and estimates synthesized in Table 2.2, p. 80, and Figure 2.3, p. 83, and discussed in the context of the results from previous continental carbon cycle synthesis efforts (e.g., CCSP 2007; Hayes et al., 2012; King et al., 2015).

Major uncertainties

The bottom-up estimate of the overall continental-scale carbon sink presented here is inferred from reconciling a number of estimates from different components, themselves often highly uncertain. Even components estimated in formal inventories (e.g., the forest sector) have pools and fluxes that are less well quantified (e.g., forest soils) and regional and temporal gaps in measurements. A large component of the uncertainty stems from limited information about the magnitude, spatial distribution, and temporal variability of carbon sources and sinks in inland, tidal, and coastal waters. Uncertainty in the top-down, atmospheric-based estimates is primarily from sparse observational networks and often poorly constrained models of atmospheric transport.

Summary sentence or paragraph that integrates the above information

In previous studies over the past decade, the larger bottom-up sink estimates have approached the lower end of the uncertainty in atmospheric model estimates (King et al., 2012). For Key Finding 5, the results presented here show further convergence between the top-down, continental-scale carbon sink estimate from atmospheric modeling and the synthesis of estimates from bottom-up approaches across the major components of North America (see Figure 2.5, p. 94).

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Section II

HUMAN DIMENSIONS OF THE CARBON CYCLE

These chapters highlight fluxes and processes in social-ecological systems, including urban areas, energy systems, agricultural enterprises, societal institutions, and lands belonging to Indigenous communities. The carbon cycle in these sectors is inextricably linked to human needs and actions as well as to societal decision-making outcomes.

Chapter 3
Energy Systems

Chapter 4
Understanding Urban Carbon Fluxes

Chapter 5
Agriculture

Chapter 6
Social Science Perspectives on Carbon

Chapter 7
Tribal Lands

3 Energy Systems

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KEY FINDINGS

1. In 2013, primary energy use in North America exceeded 125 exajoules,[1] of which Canada was responsible for 11.9%, Mexico 6.5%, and the United States 81.6%. Of total primary energy sources, approximately 81% was from fossil fuels, which contributed to carbon dioxide equivalent (CO_2e)[2] emissions levels, exceeding 1.76 petagrams of carbon, or about 20% of the global total for energy-related activities. Of these emissions, coal accounted for 28%, oil 44%, and natural gas 28% (*very high confidence, likely*).

2. North American energy-related CO_2e emissions have declined at an average rate of about 1% per year, or about 19.4 teragrams CO_2e, from 2003 to 2014 (*very high confidence*).

3. The shifts in North American energy use and CO_2e emissions have been driven by factors such as 1) lower energy use, initially as a response to the global financial crisis of 2007 to 2008 (*high confidence, very likely*); but increasingly due to 2) greater energy efficiency, which has reduced the regional energy intensity of economic production by about 1.5% annually from 2004 to 2013, enabling economic growth while lowering energy CO_2e emissions. Energy intensity has fallen annually by 1.6% in the United States and 1.5% in Canada (*very high confidence, very likely*). Further factors driving lower carbon intensities include 3) increased renewable energy production (up 220 petajoules annually from 2004 to 2013, translating to an 11% annual average increase in renewables) (*high confidence, very likely*); 4) a shift to natural gas from coal sources for industrial and electricity production (*high confidence, likely*); and 5) a wide range of new technologies, including, for example, alternative fuel vehicles (*high confidence, likely*).

4. A wide range of plausible futures exists for the North American energy system in regard to carbon emissions. Forecasts to 2040, based on current policies and technologies, suggest a range of carbon emissions levels from an increase of over 10% to a decrease of over 14% (from 2015 carbon emissions levels). Exploratory and backcasting approaches suggest that the North American energy system emissions will not decrease by more than 13% (compared with 2015 levels) without both technological advances and changes in policy. For the United States, however, decreases in emissions could plausibly meet a national contribution to a global pathway consistent with a target of warming to 2°C at a cumulative cost of $1 trillion to $4 trillion (US$ 2005).

Note: Confidence levels are provided as appropriate for quantitative, but not qualitative, Key Findings and statements.

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[1] One exajoule is equal to one quintillion (10^{18}) joules, a derived unit of energy in the International System of Units.

[2] Carbon dioxide equivalent (CO_2e): Amount of CO_2 that would produce the same effect on the radiative balance of Earth's climate system as another greenhouse gas, such as methane (CH_4) or nitrous oxide (N_2O), on a 100-year timescale. For comparison to units of carbon, each kg CO_2e is equivalent to 0.273 kg C (0.273 = 1/3.67). See Box P.2, p. 12, in the Preface for more details.

3.1 Introduction

This chapter assesses the contribution of the North American energy system to the global carbon cycle, including the identification of pathways to greater energy efficiency with lower emissions. The system—defined by energy-related activities in Canada, Mexico, and the United States—includes primary energy sources; the infrastructure to extract, transport, convert, transmit, distribute, and use these resources; and the socioeconomic and political structures and dynamics associated with these processes (Romero-Lankao et al., 2014). This definition is larger and more inclusive of socioeconomic and political components than that offered by the Intergovernmental Panel on Climate Change (IPCC; Bruckner et al., 2014). The assessment presented in this chapter includes quantitative indicators of energy use and carbon dioxide equivalent (CO_2e)

emissions from different energy system components since 2003, as well as quantitative and qualitative analysis of the changes in system dynamics, technologies, and costs for an average global warming of less than 2°C. Coverage includes 2004 to 2013, although in some cases updates to 2017 are also provided. (For a more extensive description of CO_2e, see Box P.2, p. 12, in the Preface).[3]

An important source of CO_2e emissions for the continent and the world, the North American energy system in 2013 was responsible for approximately 1.76 petagrams of carbon (Pg C), or 20% of global energy-related emissions (EIA 2016c).[4] From 2004 to 2013, the system experienced significant changes that have affected the North American contribution to CO_2e emissions. These changes include alterations to the fossil fuel mix, increases in renewable energy sources, advances in production efficiencies, an economic shock from the global financial crisis (GFC) of 2007 to 2008, changing fuel prices, and changing carbon management policies. These trends and drivers of change may continue to influence energy-related carbon emissions in the coming decades.

The historical context for North American energy use and CO_2e emissions is described in Section 3.2, this page, emphasizing dynamics associated with previous large fluctuations in carbon emissions. Section 3.3, p. 113, details the state of the energy system as of 2013, including 1) an overview of energy infrastructure; 2) overall energy resources and uses; 3) technologies to increase efficiency and reduce emissions such as total CO_2e emissions, by economy; and 4) end use (e.g., buildings, industry, and transportation) and secondary energy use (electricity). Section 3.4, p. 126, discusses five important patterns and dynamics of the North American energy system that have emerged since the *First State of the Carbon Cycle Report* (SOCCR1; CCSP 2007). Section 3.5, p. 140, places the North American energy system in a global context, in terms of both energy use and CO_2e, while Section 3.6, p. 140, presents an examination of drivers, based on the Kaya Identity.[5] Governmental policy drivers, including carbon management decisions, are the focus of Section 3.7, p. 149, followed by a comparison in Section 3.8, p. 154, of selected recent scenario results to 2040 and 2050 of energy use and CO_2e emissions for the Canadian, U.S., and Mexican economies including projections as well as exploratory and backcasting approaches. The final section (Section 3.9, p. 167) synthesizes the information, identifies knowledge gaps, and summarizes key challenges.

3.2 Historical Context

Given the recent trends in the region's energy use and CO_2e emissions, examining past emissions fluctuations and their relationship to social and economic trajectories is useful for understanding the current situation as well as the range of plausible energy and CO_2e emissions futures.[6] Historically, North American energy use and carbon emissions fall for short periods of time after major societal shocks. For example, energy use and emissions levels peaked in North America around 1929, subsequently fell during the Great Depression, and did not exceed the 1929 peak until around 1941. From the late 1950s to the early 1970s, emissions from fossil fuel burning grew as energy demand rapidly increased. From 1960 to 1973, total final energy

[3] In addition to the definition of CO_2e in the Preface, natural gas values in this chapter do not include methane emissions during production from coal mines, oil or gas wells, or abandoned mines and wells.

[4] Consistent with formatting in the *Second State of the Carbon Cycle Report* (SOCCR2), this chapter presents emissions data in grams (g) and the International System of Units for multiples of grams—teragram (Tg): a unit of mass equal to 10^{12} grams = 1 million metric tons (Mt); petagram (Pg): a unit of mass equal to 10^{15} grams = 1 billion metric tons. Petagrams of carbon (Pg C) = gigaton of carbon (Gt C); teragrams of carbon (Tg C) = million metric tons of carbon = megaton of carbon (Mt C); Tg C = 10^{12} grams = 10^6 ton.

[5] The Kaya Identity is an accounting technique that includes factors, sometimes called "immediate drivers," that connect with or represent a larger number of underlying drivers, such as processes, mechanisms, system characteristics, policies, and measures (Blanco et al., 2014).

[6] For a broader historical examination of the North American energy system and its relationship to the carbon emissions, see Pacala et al. (2007) and Marland et al. (2007).

use[7] for North America increased from 36 exajoules (EJ) to more than 62 EJ, or by 70% (IEA 2016d).[8] During this period, CO_2e emissions from energy increased from 859 teragrams of carbon (Tg C) to 1.45 Pg C, or by more than 68%. This was an exceptional period, in terms of both absolute increases and the energy–economic output relationship. Then, because of "oil shocks," restructuring of the global economy, and other factors including an economic recession, total North American final energy use fluctuated, slowly increasing to reach a new high of about 66.3 EJ in 1979 before falling again in 1980. Thereafter, total final energy use remained below the 1979 record-high, increasing throughout the 1980s. Energy use and emissions increased over this period, falling again in the early 1990s during a short economic recession. Rebounding almost 14 years after the large fall in 1980, North American final energy use reached a new record-high in 1993. After that time, North American energy use started to increase monotonically again. From 1994 to 2007, both total final energy use and CO_2e emissions followed an increasing trend. By 2007, total North American energy use had reached 128 EJ, and CO_2e emissions approached 1.86 Pg C. The 2007 to 2008 GFC marked the beginning of another decreasing trend, as North American CO_2e emissions, primary energy use, and total final energy use dropped below the 2007 peak and remained below it through 2015 (Boden et al., 2016; EIA 2016c; IEA 2016d).

The historical trajectories of energy use, CO_2e emissions, and economic fluctuations seem to move together, and, if previous average trends portend system response, North American energy use can be expected to rebound from its current trend and exceed the previous peak energy use and emissions levels by around 2020. Recent detailed examinations of the U.S. historical trends, however, suggest that since 1949, there appears to be a shift from a path that closely maps gross domestic product (GDP) with energy use and CO_2e emissions to a divergence of these trends, and this divergence became particularly evident after 1972 (see Figure 3.1, p. 114). Further research suggests that structural changes in the energy and economic systems are reducing the growth of emissions, such that emissions are contracting during recessions faster than they increase during economic expansions. Thus, the rate of increase of CO_2e emissions during the expansion phase continues to be substantially reduced, and this has been particularly noticeable since the early 1990s contraction (Burke et al., 2015b; Shahiduzzaman and Layton 2015). The dynamics underpinning the most recent trends are examined in this chapter and may signal shifts in the energy–economic growth relationship, implying the potential for future new energy and emissions patterns.

3.3 North American Energy System

This section presents a description of the state of the North American energy system by first identifying the size of the system in terms of population and economy, energy resources, and primary energy supply. End-use sectors of buildings, industry, and transportation, along with electricity generation, are then discussed and their regional contributions to the carbon cycle evaluated. Technologies for increasing efficiencies and lowering emissions levels are briefly described for each sector. The last subsection describes promising technologies for increasing carbon sinks.

[7] Energy end use includes all energy supplied to the consumer for services, such as motive power, cooking, illumination, comfortable indoor climate, and refrigeration. Energy end use typically is disaggregated into end-use sectors: industry, transport, buildings (residential and commercial), and agriculture. It is differentiated from energy supply, which consists of all energy used in a sequence of processes for extracting energy resources, converting them into more desirable and suitable forms of secondary energy (i.e., electricity and heat), and delivering energy to places where demand exists. Primary energy is the energy embodied in resources as they exist in nature, and final energy is the energy transported and distributed to the point of users (e.g., firms, individuals or organizations) (Grubler et al., 2012).

[8] Energy is measured with different units such as joules (J), British thermal units (BTUs), tons oil equivalents (toe), gigawatt hours (GWh), barrels of oil (BBL), and billion cubic feet (ft^3) of natural gas (BCF). This chapter refers to energy use in joules (J) and the International System of Units for multiples of joules: kilojoule (kJ) = 10^3 J, megajoule (MJ) = 10^6 J, gigajoule (GJ) = 10^9 J, terajoule (TJ) = 10^{12} J, petajoule (PJ) = 10^{15} J, exajoule (EJ) = 10^{18} J, and zettajoule (ZJ) = 10^{21} J.

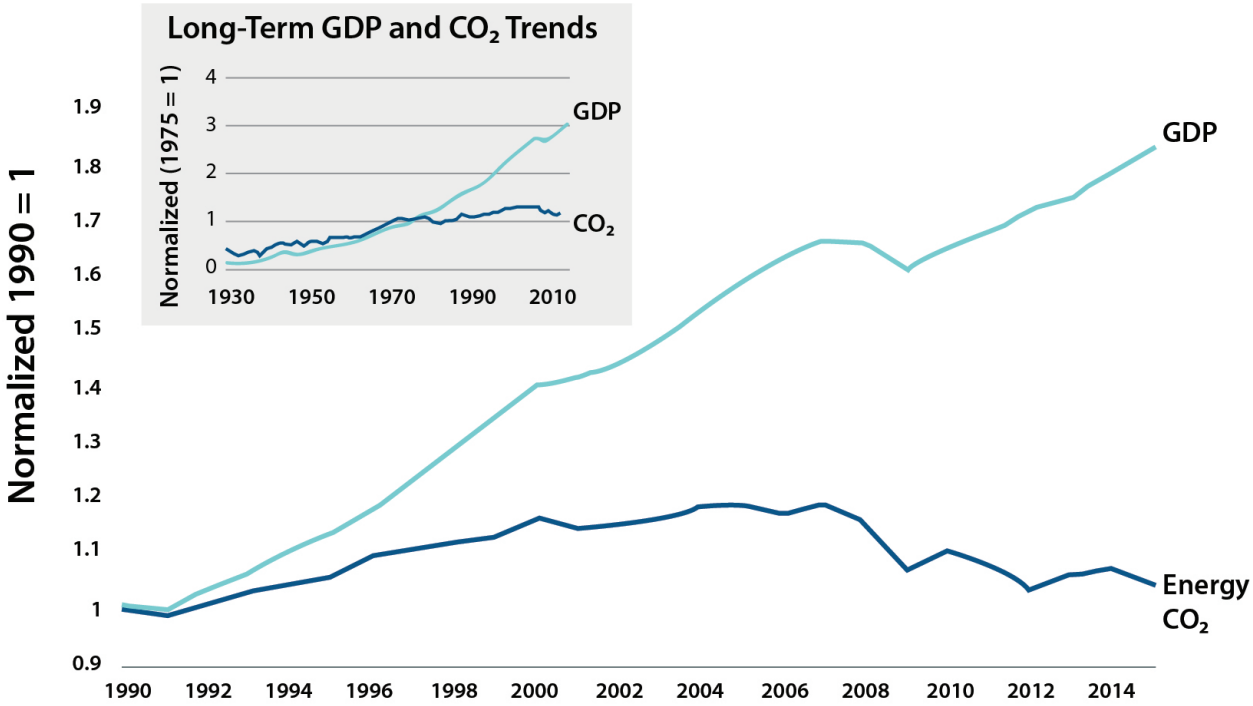

Figure 3.1. U.S. Energy Carbon Dioxide (CO_2) Emissions and Gross Domestic Product (GDP).

The data compiled for this assessment come from a variety of sources, which have different methods of estimating and reporting energy use and emissions levels. For example, the International Energy Agency (IEA) of the Organisation for Economic Cooperation and Development (OECD) reports energy consumption on a net calorific value (or low heat value), while the U.S. Department of Energy's (U.S. DOE) Energy Information Administration (EIA) and Canada report on a gross calorific value (or high heat value; IEA 2016c). (For a discussion of the different inventories and their sectoral scope and methodologies, see Appendix E: Fossil Fuel Emissions Estimates for North America, p. 839.) This section presents data as consistently as possible, using ranges when there is significant disagreement between numbers. When possible, sources are combined using national data to present absolute values for energy and emissions from end-use sectors, and international sources are used in presenting shares of regional totals.

3.3.1 Size of the North American Energy System

By 2013, the North American energy system was serving around 491 million people, or about 6.7% of the global population (UN 2015). Of North America's population, Canada contributed 7%, Mexico 26%, and the United States 67% (UN 2015). According to the World Bank (2016a), North America in 2013 had a combined GDP of more than $19.7 trillion (constant US$ 2010), almost 26% of world GDP. Within North America, the approximate 2013 GDP per capita was $49,200 for Canada, $49,900 for the United States, and $9,300 for Mexico (constant US$ 2010).

The World Energy Council (2016a) and BP (2017b) have identified massive fossil fuel energy reserves in North America (see Table 3.1, p. 115). "Proven" or "proved" coal reserves exceed 7.2 zetajoules (ZJ), accounting for more than 27% of the world share in 2015 (for definitions of reserves and resources, see

Table 3.1. North American Proven Energy Reserves (2015)[a]

Country or Region	Coal Recoverable Reserves	Oil Recoverable Reserves	Gas Recoverable Reserves
Canada	193.0 EJ[b]	1,163.9 EJ	74.9 EJ
Mexico	35.9 EJ	62.8 EJ	12.2 EJ
United States	6,950.1 EJ	276.7 EJ	393.6 EJ
North America	7,201.3 EJ	1,503.1 EJ	481.5 EJ
North America Share of Global	27.5%	14.0%	6.8%
R/P[b] (Years)	276.0	33.1	13.0

Notes

a) Sources: BP (2016); World Energy Council (2016a).

b) EJ, exajoule; R/P, reserve-to-production ratio.

Box 3.1, Energy Resources and Reserves, p. 116). Most North American coal is high quality: 46% is bituminous, 40.7% subbituminous, and only 13.2% lignite, which has the lowest heat content of the three types of coal (World Energy Council 2013). The majority of these coal reserves, almost 6.95 ZJ, are in the United States, which produced 23.8 EJ of coal in 2015. This production represents a 10.4% decline from 2014, as coal consumption has decreased by 20% from 2011 levels (Houser et al., 2017). Canada's coal deposits, most of which are in the western provinces, are significant as well, reaching 193 EJ. Mexico's coal reserves are small by comparison, totaling 37 EJ. At current production rates, North America has more than 270 years of proven coal reserves.

The continent's proven oil reserves amounted to 1.5 ZJ in 2011, or more than 12% of the global total in 2015. Canada's oil reserves, the largest in North America, are the third largest in the world after Saudi Arabia and Venezuela. Particularly significant to the carbon cycle are Alberta's oil sands, which underlie 142,000 km^2 of land in the Athabasca, Cold Lake, and Peace River areas in the northern part of the province. Mining and processing this unconventional source of oil currently account for approximately 8.5% of Canada's total CO_2e emissions (Government of Alberta [Canada] 2016). Oil sands also now represent about 98% of Canada's growing oil reserves and about half the country's production in 2011. Despite this large reserve, in 2015 the United States produced 23.7 EJ, more than twice as much as Canada's production of 9.04 EJ. The United States also has developed unconventional technologies for extracting oil, including from shales. Proven oil reserves in the United States increased by 57% from 2005 to 2015 (EIA 2016k), and by 2012 shale oil accounted for about 22% of those reserves (EIA 2014a). Mexico's oil reserves have decreased over the past decades. Although the country's Cantarell oil field is one of the largest in the world, production has declined since 2003. In 2011, Mexico's oil reserves were 62.8 EJ. According to BP (2016), oil reserves within the country have fallen from 285 EJ in 1995. Mexican oil production has been relatively stagnant since 2009 (World Energy Council 2016a). Overall, the North American share of total global proven oil reserves was 14% in 2016, with a projected use of more than 32 years of reserves under current conditions (BP 2017b).

In 2015, North America's proven natural gas reserves reached 482 EJ. The United States has about 82% of the total proven natural gas reserves in North America, and the continent has approximately 6.8% of world reserves. As with oil, unconventional extraction techniques have expanded the region's reserves dramatically. Over the last 10 years, shale gas reserves in the United States have increased

Box 3.1 Energy Resources and Reserves

Fossil fuels are abundant in many regions of the world including North America. To provide an understanding of their quantity and quality for various purposes, energy analysts classify them according to availability. Classification systems typically divide *resources* from *reserves*. This distinction reflects the likelihood that the fossil fuels will be brought to the market. Energy resources include volumes that have yet to be fully characterized, present technical difficulties, or are costly to extract. For example, there are existing resource volumes for which technologies have yet to be developed that permit their extraction in an environmentally sound and cost-effective manner. Reserves include volumes whose production can be achieved economically using today's technology. Often associated with ongoing production projects, energy reserves are further classified as "proven" (proved) and "unproven" (unproved). Proven reserves are those with a reasonable certainty (a minimum 90% confidence) of being recoverable under existing economic, technological, and political conditions. Unproven reserves include sources that have a lower probability of being produced (IEA 2013).

To provide information on future availability of nonrenewable energy reserves, analysts typically use reserve-to-production ratios (RPR or R/P), which are expressed in years. The denominator is the production rate of the reserve during the latest years. The reserve typically includes proven amounts. In the United States, however, resource categories are expressed as "proved," "economically recoverable resources," and "technically recoverable resources" (see Figure 3.2, this page). Using this extended definition increases the years of calculated use of the fuel. That is, the length of time that a resource is available often

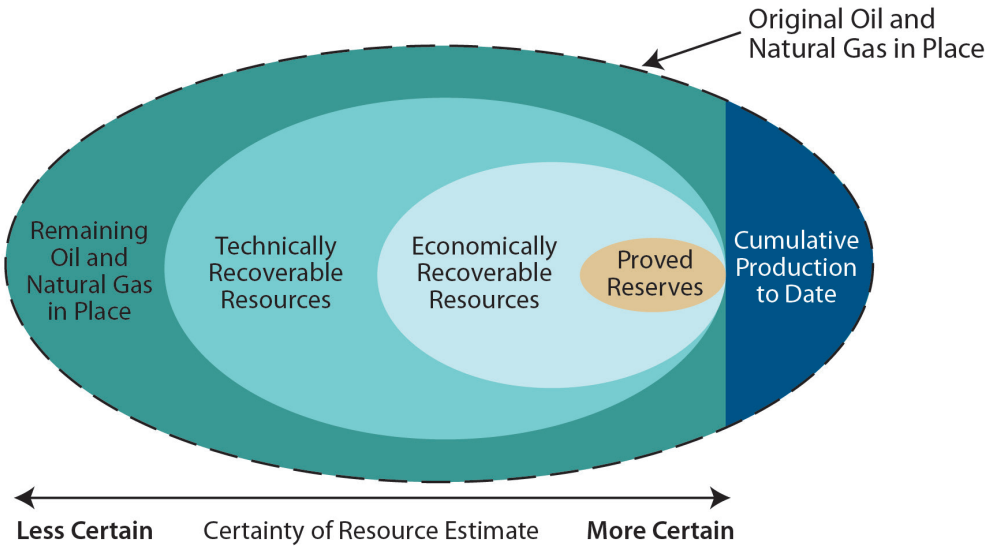

Figure 3.2. Stylized Representation of Oil and Natural Gas Resource Categories. Figure is not to scale. [Figure source: Redrawn from EIA 2014b.]

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is expressed in terms of a ratio of the proved reserve to the amount consumed annually. This U.S. ratio includes the technically recoverable resource to the amount consumed annually (EIA 2014b). Technically recoverable resources, consisting of both proved and unproved reserves, include all the oil and gas that can be produced based on current technology, industry practice, and geological knowledge. As technology develops, industry practices improve. As understanding of the geology increases, the estimated volumes of technically recoverable resources also expand. Each year, the U.S. Department of Energy's Energy Information Administration (EIA) reports proved U.S. oil and natural gas reserves and its estimates of unproved technically recoverable resources for shale gas, tight gas, and tight oil resources. These reserve and resource estimates are used in developing EIA's *Annual Energy Outlook* projections for oil and natural gas production. In 2015, for example, estimates for oil in the United States suggest approximately 244 exajoules (EJ) of proved reserves of oil and 1.4 zettajoules (ZJ) of unproved resources, for a total of 1.7 ZJ of technically recoverable resources. For natural gas, the United States has about 369 EJ of proved reserves and 2.1 ZJ of unproved reserves, for a total of 2.5 ZJ of technically recoverable resources (EIA 2017k). Economically recoverable resources are the amounts of technically recoverable resources that can be profitably produced. The volume of economically recoverable resources is determined by both oil and natural gas prices and by the capital and operating costs that would be incurred during production.

For consistency across economies, this chapter uses proven reserves and expresses availability in R/P ratios. However, the differences are noted when these figures conflict with numbers provided by individual nations.

ninefold. As of 2015, the United States produces 22% of the world's natural gas and Canada produces almost 5%. Mexico also has increased gas production over the past decade, producing as of 2015 about 1.5% of the world's natural gas (BP 2016). North American proven gas reserves are projected to last another 13 years under current production conditions. However, the United States estimates its national gas reserves will last another 86 years. These estimates disagree because of different definitions of reserves (see Box 3.1, p. 116). While international analysis typically uses proven reserves to estimate how long an energy reserve will last, the United States uses both proven and unproven technically recoverable resources (EIA 2017e).

The concept of proven reserves is mainly for stock accounting that energy entities maintain to ensure adequate production in the near future. At a global scale, for example, proven oil reserves relative to current production have changed very little over decades. Resources have various definitions, but as a very broad generalization, technological advances have consistently overcome depletion of fossil fuel reserves. This outcome is likely to continue over the short to medium term. Using regional proven reserves, however, holds tremendous potential for increasing the atmosphere's carbon concentration.

In 2013, the three economies of North America had a combined total energy use that exceeded 125.6 EJ (EIA 2016c), or approximately 22% of global primary energy use. Of the total, Canada was responsible for approximately 11.9% (14.9 EJ), Mexico 6.5% (8.2 EJ), and the United States 81.6% (102.6 EJ). The per capita energy-use levels are relatively similar between the United States and Canada but different for Mexico. For example, according to the World Bank (2016a), in 2015, energy use per capita in Canada and the United States was 318 gigajoules (GJ) and 284 GJ, respectively, while Mexico's was about 62 GJ.

Table 3.2 North American Nonfossil Fuel Electricity Capacity (2015)[a]

Area	Hydro-Installed Capacity (GW)[b]	Solar-Installed Capacity (GW)[b]	Geothermal-Installed Capacity (GW)[b]	Wind-Installed Capacity (GW)[b]	Nuclear-Installed Capacity (GW)[b]
Canada	79.2	2.2	1.5	11.2	13.5
Mexico	12.4	0.2	1.1	3.1	1.4
United States	102.0	27.3	3.6	72.6	99.2
North America	193.0	29.8	23.7	86.9	114.1

Notes

a) Sources: BP (2016); World Energy Council (2016a).

b) GW, gigawatts.

Although about 81% of North America's total energy use is from fossil fuels, the continent also has significant renewable and low-carbon inputs to the electricity system (see Table 3.2, this page). These include 1) the world's leading installed hydropower capacity; 2) 13% of the world's solar capacity; 3) 28% of the global geothermal capacity; 4) approximately 86.9 gigawatts (GW) of wind capacity, which is rapidly increasing (e.g., 8.6 GW of wind power installed by the United States in 2015, a 77% increase from 2016); 4) significant nuclear capacity at approximately 114 GW (i.e., 29% of global nuclear capacity and 36% of global nuclear generation in 2016; Nuclear Energy Institute 2017; IAEA 2017); and 5) uranium resources estimated at 0.82 Tg (World Energy Council 2016a). Changes in the regional renewable energy generation capacity, via increases in renewable resources, are having significant effects on the regional energy system's contribution to the carbon cycle (for a discussion of the renewable resources in the region, see Section 3.4.3, p. 131, and Section 3.6.4, p. 147).

Fossil fuel combustion contributes considerably to the global carbon cycle. In 2013, North American CO_2e emissions from fossil fuel combustion exceeded 6.45 Pg CO_2e (1.76 Pg C). These emissions, down approximately 11% from 2007 levels, represent about 20% of the global total for energy-related activities (see Section 3.4.1, p. 127, for details). Among North American CO_2e emissions from fossil fuels, coal accounted for 28%, petroleum 44%, and natural gas 28%. Energy-related CO_2e emissions exceeded 5.4 Pg (1.47 Pg C) for the United States and 0.56 Pg (153 Tg C) for Canada and were about 0.45 Pg (123 Tg C) for Mexico (EIA 2016f). For 2013, the World Bank (2016b) estimated that CO_2e emissions per capita from energy use were 18.8 Mg (5.1 Mg C) for the United States; 15.3 Mg (4.17 Mg C) for Canada; and 6.5 Mg (1.77 Mg C) for Mexico, well below the averages for the two other countries.

3.3.2 North American Subsystem Contributions to Carbon Emissions

The North American subsystems include residential and commercial buildings, industry, and transportation end-use sectors along with the electricity-generation sector. Each subsystem is described in this section by identifying its major components, followed by a description of primary energy source contributions, the total energy use within the sector in 2013, and related carbon emissions during that year. Each energy sector description includes sector characteristics of each of the three nations defined as the "region," concluding with a brief overview of new and emerging technologies that increase efficiencies and lower carbon emissions. The final part attempts to synthesize much of this information through the presentation

and discussion of energy and CO_2e emissions flow diagrams specific to the U.S. energy system.

Electricity

The North American electric power system is integrated through more than 35 transmission interconnections between Canada and the United States and about nine between Mexico and the United States (CEA 2014). The U.S. electrical system is the largest within North America, including more than 7,700 power plants, 1.1 million km of high-voltage transmission lines, 10.5 million km of distribution lines, and almost 56,000 substations (U.S. DOE 2017d) with over 1 billion kilowatts (kW) of installed generating capacity (CIA 2018). The Canadian electrical system has more than 1,700 power plants (CGD 2016), over 160,000 km of transmission lines (IEA 2010), and about 148 million kW in installed generating capacity (CIA 2018). Mexico's energy system is also large, expanding and integrating with the U.S. system and containing about 400 thermal power plants (CGD 2012) with over 65 million kW in installed generating capacity (CIA 2018). Mexico's national transmission grid includes approximately 50,000 km of mostly high- and medium-voltage lines, and the country is constructing dozens of new natural gas–fired power plants to meet increasing electricity demand (EIA 2016j).

In 2013, North America generated 17.9 EJ of electricity, 18% of which was from nuclear power, 14% from hydropower, 6% from nonhydroelectric renewables, and 62% from fossil fuels, with about 7% of this total lost in transmission and distribution. Within North America, Mexico was responsible for 5.6% of the continent's total electricity generation, Canada 12.8%, and the United States 81.5%. Together, the total electricity generated by these countries in 2013 was approximately 22.5% of the global total (EIA 2016c).

The U.S. electricity sector contributed about 34% of total national CO_2e emissions, or 556 Tg C, in 2013 (U.S. EPA 2016). In Canada, electricity generation accounted for approximately 12% of national CO_2e emissions, or 85 Tg CO_2e (23 Tg C; ECCC 2016b). Canada's lower share of national emissions from electricity generation is due to the high share of hydropower in electricity generation as well as the high-carbon intensity (see Section 3.6.3, p. 144) of the country's other sectors. According to SEMARNAT-INECC (2016), the Mexican electricity sector emitted approximately 127 Tg CO_2e (34.6 Tg C) in 2013, or about 26% of net national CO_2e emissions. Recently, however, the Mexican government ended its state-owned electricity monopoly and subsequently held the first power auction in 2016, awarding more than 1.7 GW to solar and wind generation (Meyers 2016), suggesting changes in the future.

Emerging trends have been stressing the North American electricity sector. This system was not designed for the distributed and often nondispatchable generation (electrical energy that cannot be turned on or off to meet demand fluctuations) that is dominating electricity supply growth, the electrification of the transportation and low-temperature heat markets, and the effects of climate change itself. Although challenging, this changing landscape provides opportunities for increased efficiencies and lower emissions levels achievable through a number of energy-sector advances. These improvements include 1) grid modernization, 2) applications of intelligent technologies and next-generation components with "built-in" cybersecurity protections, 3) advanced grid modeling and applications, 4) distribution generation and innovative control system architectures, and 5) improved storage capacity (U.S. DOE 2017d). New energy storage technologies, including batteries to overcome solar and wind intermittency challenges, can help make these technologies directly competitive with fossil-based electricity options (Kittner et al., 2017). Advances in nuclear power such as small- and medium-sized and modular technologies offer opportunities to increase the already large fleet of plants, although the future of this technology remains unclear (see Box 3.2, Potential for Nuclear Power in North America, p. 120, and Section 3.4.4, p. 134).

Box 3.2 Potential for Nuclear Power in North America

Nuclear energy, generated from around 450 power reactors in 31 countries, has provided around 10% to 11% of the world's power generation over the past several years; nearly half the current global nuclear generation is from the United States and France, and another 20% is from China, Russia, and South Korea (Schneider et al., 2017). Except for China—which increased its nuclear generation by 23% from 2015 to 2016—the world is closing plants at a similar rate to building new ones (World Nuclear Association 2018). This is due partly to relatively expensive capital and operational costs and public fears of safety, but also to slow construction times with frequent delays. For example, average plant construction is around 7 years, and two new plants, one in Argentina and the other in the United States, took over 30 years each to complete (Schneider et al., 2017; The Economist 2017).

In North America, Canada currently has 19 nuclear reactors in operation supplying 344.5 petajoules (PJ) of electricity. Mexico has two reactors supplying 37.1 PJ of electricity, and the United States has around 99 reactors in 30 states supplying 2.9 exajoules of electricity (IAEA 2017). The current nuclear energy generated accounts for about 18% of electricity for the region. Within the region, the United States is the only economy with plans to expand its nuclear reactor fleet, partly in an effort to overcome decommissioning trends. For example, since 2013, five U.S. nuclear reactors have shut down and nine others supplied closure announcements, while five new nuclear reactors are scheduled to come online by around 2019 (White House 2016). Two nuclear reactors are actively under construction: Vogtle Units 3 and 4 in Georgia. They were the first new reactors to receive construction approval in more than 30 years, and their construction has been buffeted by delays and cost overruns.

Nuclear is often considered a key component of a high-energy, low-carbon future (e.g., Bruckner et al., 2014; NEA 2012). In the United States, for example, nuclear energy currently provides about 60% of national carbon-free electricity (White House 2016). New designs, such as small- and medium-scale and modular systems are innovations that address reductions in greenhouse gas emissions and extend nuclear power into other applications, such as heat for industrial processes and use in desalination plants (IAEA 2017; Rosner and Goldberg 2011). Current trends in small and modular systems, however, suggest that global interest in these technologies has faded (Schneider et al., 2017).

For nuclear power to be viable, reactors need to be fundamentally transformed, overcoming several challenges: 1) costs need to come down and be competitive with other energy sources; 2) development of plants needs to be quicker; 3) safety concerns need to be addressed; 4) opportunities for nuclear in areas with no preexistent nuclear power need to be explored; and 5) issues related to waste and national security need to be resolved (CATF 2018). Related to these challenges, the expansion of this industry requires changes in regulatory structures including licensing, design certifications, and control procedures and requirements. Moreover, there also are environmental justice issues surrounding uranium mines in the region. For example, about 75% of the 15,000 U.S. uranium mine locations are on federal and tribal lands, where mining activities have created significant health issues for Native Americans (Moore-Nall 2015) and extremely long-term ecological degradation (see Ch. 7: Tribal Lands, p. 303, for a discussion of the specific tribal land location of regional energy reserve shares and their impacts).

To address some of these issues, industry leaders and start-up companies have developed

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advanced designs and features for future nuclear reactors intended to address these barriers (CATF 2018). Advanced reactors employ different fuels and technologies that 1) reduce waste (e.g., via more efficient fuel use); 2) reduce costs (e.g., via coolants that require less materials for containment); 3) are faster to build (via smaller, segmented reactors built offsite and shipped to destination); 4) decrease the risk of weapons proliferation (via less desirable fuels and waste streams); and 5) improve safety (via nonwater coolants and stations on floating platforms at sea). While innovative reactor technologies are currently available, they will not be commercially scalable for rapid nuclear expansion across North America and the rest of the world without further research and development (CATF 2018; U.S. DOE 2017c).

Residential and Commercial Buildings

North America's building stock varies in quantity and quality. In 2013, Canada had 14.8 million residential households occupying over 2 billion m^2, plus 480,000 commercial buildings with 739 million m^2 of floor space (Natural Resources Canada 2015; Natural Resources Canada 2018a). Mexico had an estimated 28 million residential households and 25.5 million m^2 of commercial floor space (UNEP 2009). The U.S. had 114 million residential households occupying almost 18 billion m^2 (EIA 2015b) and more than 5.5 million commercial buildings with a total floor space of over 8 billion m^2 (EIA 2012c).

In 2013, the North American commercial sector used about 9.7 EJ of energy, mostly from electricity (58%), natural gas (37%), and oil products (7%). Residential buildings used about 13.3 EJ in 2013, supplied mostly by electricity (43%), natural gas (41%), heating oil (8.7%), and biofuels and waste (6.4%) (IEA 2016d). Given the large building stock in the region, the residential and commercial buildings sector accounts for a large share of energy use. In Canada, Mexico, and the United States, commercial and residential building operations account for about 20%, 30%, and 40%, respectively, of each country's primary energy consumption.

Much of the energy use in buildings is from electricity and natural gas. In 2013, U.S. buildings consumed 73% of the country's electricity and 52% of direct natural gas (60% of which was for electricity generation; EIA 2015b). In the residential sector, a significant fraction of overall energy consumption is for space heating and air conditioning, although in the United States the share of heating and cooling has dropped from 58% in 1993 to 48% in 2009 (EIA 2013a). The main U.S. sources of heating during the winter months are natural gas or electric furnaces and electric heat pumps, but the range of equipment and fuels varies across climate regions (EIA 2017h). Energy consumption for appliances and electronics continues to rise, signaling the importance of nonweather-related energy use in homes (EIA 2013a). In Canada, approximately 63% of residential energy use is for space heating, with another 24% for water heating (Natural Resources Canada 2016c; Natural Resources Canada 2018b).

Alternatively, removing electricity-related emissions from the buildings sector makes the sector's share of CO_2e emissions across the region the lowest among end-use sectors. For example, in 2013, the U.S. commercial and residential sectors together accounted for 10% of total national CO_2e emissions (U.S. EPA 2016; see Figure 3.3, p. 125). The U.S. commercial sector emitted approximately 59 Tg C, and the residential sector was responsible for about 89.5 Tg C. The Canadian buildings sector emitted 74 Tg CO_2e (20.2 Tg C), or 10% of total national emissions (ECCC 2016b). In Mexico, the buildings sector emitted about 25.6 Tg CO_2e (7.0 Tg C) in 2013, representing about 5% of total net national emissions for that year (SEMARNAT-INECC 2016).

Technological opportunities for improved energy efficiency and reduced carbon emissions from the building sector are extensive. By 2030, building energy use could be cut more than 20% using known cost-effective technologies. The United States identified potential technological improvements for the residential and commercial sectors, including high-efficiency heat pumps, thin insulating materials, windows and building surfaces with tunable optical properties, high-efficiency lighting devices, and low-cost energy-harvesting sensors and controls (U.S. DOE 2015a). Many of these technologies address thermal properties of buildings and technologies for space heating and cooling energy services, thus effectively reducing electricity and natural gas usage.

Industry

The extremely diverse North American industrial sector consists of mining, manufacturing, and construction. Mining enterprises extract raw materials from Earth's crust that are used as inputs for manufacturing and construction. Construction enterprises create North America's built environment, including buildings, industrial facilities, and infrastructure such as roads and the electric power grid. Manufacturing consists of a wide variety of small, medium, large, and very large facilities with subsectors including iron and steel, chemicals and petrochemicals, nonferrous metals, nonmetallic minerals, transport equipment, machinery, food and tobacco, paper, pulp and printing, wood and wood products, textile and leather, and nonspecified industry.

Manufacturing, in particular, represents a complex and diverse sector that both contributes to CO_2e emissions and offers the potential for reductions over the lifetime of manufactured products and materials. Manufacturing involves global supply chains of raw materials, processed materials, components, and final products that are sourced and traded globally. Manufacturing's complex supply and trade networks are exemplified in a case study by the Clean Energy Manufacturing Analysis Center (CEMAC) describing a typical solar crystalline silicon photovoltaic (PV) panel, a clean energy technology that reduces emissions from power production. This solar end product includes polysilicon made in the United States and exported to many other countries (US$1.8 billion in total exports in 2014). These countries then make PV cells and modules that are re-imported back to North America (US$3.9 billion; CEMAC 2017). Another example is the manufacture of turbine components (e.g., nacelles and blades) in the United States from steel and other materials from multiple sources; the parts are then installed in the United States and also exported (US$0.4 billion) to Canada, Brazil, and Mexico. Because these complex supply and trade networks are not comprehensively understood, further study could play an important role in supporting efforts to reduce emissions from industrial end uses.

In 2013, the total energy use for the North American industrial sector was about 14.7 EJ. The major energy sources for industry included natural gas (40%), electricity (29%), biomass and wastes (11%), oil and oil products (10%), coal (8%), and heat (2%; IEA 2016d). Additionally, about 6.11 EJ were consumed as industrial nonenergy use, or feedstock, major sources of which included oil and oil products (88%) and natural gas (12%; EIA 2016i). For the North American agriculture and forestry sectors, total energy use was approximately 1.3 EJ, supplied mostly by oil and oil products (76%), electricity (15%), natural gas (6%), and biomass and wastes (3%; EIA 2016i). The United States consumed 17.2 EJ, representing 78% of this sector's total energy and feedstock consumption in North America in 2013.

In 2014, IEA reports that the total North American industrial sector emitted 1.65 Pg CO_2e (450 Tg C), of which the United States contributed 1.24 Pg CO_2e, or 338 Tg C (IEA 2016d). Based on a comparison of U.S. DOE datasets for U.S. industrial sector emissions and the World Resources Institute's CAIT database for CO_2e emissions, the industrial sectors in Canada, Mexico, and the United States in 2012 emitted approximately 0.19 Pg CO_2e (51.8 Tg C), 0.17 Pg CO_2e

(46.4 Tg C), and 1.63 Pg CO_2e (445 Tg C), respectively. These estimates represent 27%, 24%, and 26%, respectively, of each country's total energy sector CO_2 emissions in 2012. By comparison, U.S. DOE reported 1.5 Pg CO_2e (410 Tg C) for the United States, Natural Resources Canada reported 0.179 Pg CO_2e (48.8 Tg C) for Canada, and the National Institute of Ecology and Climate Change (INECC) reported 0.115 Pg CO_2e (6.4 Tg C) for Mexico in 2013. If electricity-related emissions are excluded from the industrial sector, U.S. industrial emissions were approximately 264 Tg C and Canada's industrial emissions were about 41 Tg C in 2013. Both sets of values have remained at these respective levels through 2015 (EIA 2018e; Natural Resources Canada 2018c). In Mexico, INECC separates electricity emissions from other sectors (SEMARNAT-INECC 2016).

State-of-the-art technologies available today could provide energy savings for the manufacturing sector, although many have not yet penetrated the market. Clean energy manufacturing includes the minimization of energy and environmental impacts from the production, use, and disposal of manufactured goods. These technologies exist for a broad range of services, such as operations to convert raw materials to finished products, effective management of the use and flows of energy and materials at manufacturing facilities, and innovative new materials and new manufacturing technologies for products that affect supply chains (U.S. DOE 2015b).

Transportation

North America has a vast, extensive transportation infrastructure. The U.S. interstate highway system is about 77,000 km long (second in length only to China's), and the country's road system covers more than 6.5 million km and includes over 600,000 bridges. This infrastructure provides the nation's nearly 11 million trucks and over 250 million passenger vehicles (WardsAuto 2015) with direct access to ports, rail terminals, and urban areas. In addition to its more than 600 smaller harbors, the United States has over 300 commercial harbors that support more than 46.4 million twenty-foot equivalent units (TEUs) of annual port container traffic (World Bank 2016c).[9] There are 3,330 existing public-use airports in the United States composing the National Plan of Integrated Airport Systems, which supports more than 9.5 million registered annual carrier departures worldwide (World Bank 2016c). Finally, the U.S. rail network includes approximately 260,000 km of track, 76,000 rail bridges, and 800 tunnels that help move both passengers and freight around the country (ASCE 2013).

Canada's transportation infrastructure includes more than 1.3 million km of public roads, 38,000 km of which are in the National Highway System used by about 1 million trucks and 20.1 million passenger vehicles (WardsAuto 2015). The country has more than 560 port facilities supporting over 5.5 million TEUs of annual port container traffic (World Bank 2016c), 900 fishing harbors, and 202 recreational harbors. Canada's 26 major airports are part of the National Airport System, which supports more than 1.2 million registered carrier departures worldwide every year (World Bank 2016c). In addition, there are 71 regional and local airports; 31 small and satellite airports; and 13 remote airports, including 11 in the Arctic. The Canadian rail system includes 45,700 km of track (Transport Canada 2015).

Mexico has a road network of more than 365,000 km used by 8.8 million registered trucks and more than 22.9 million passenger cars (WardsAuto 2015). The country also has approximately 110 major airports that carry out more than 470,000 registered carrier departures worldwide yearly, and its 76 seaports and 10 river ports support over 5.2 million TEUs of port container traffic annually (World Bank 2016c). Railroads in Mexico's estimated 26,700-km railroad network generally operate within cities, such as Mexico City and Guadalajara. A proposed high-speed rail link would connect these two cities with other locations across the country.

[9] TEUs are standardized measures of a ship's cargo-carrying capacity. The dimensions of one TEU are equal to that of a standard 20-foot shipping container (i.e., 20 feet long by 8 feet tall). Usually nine to 11 pallets fit in one TEU.

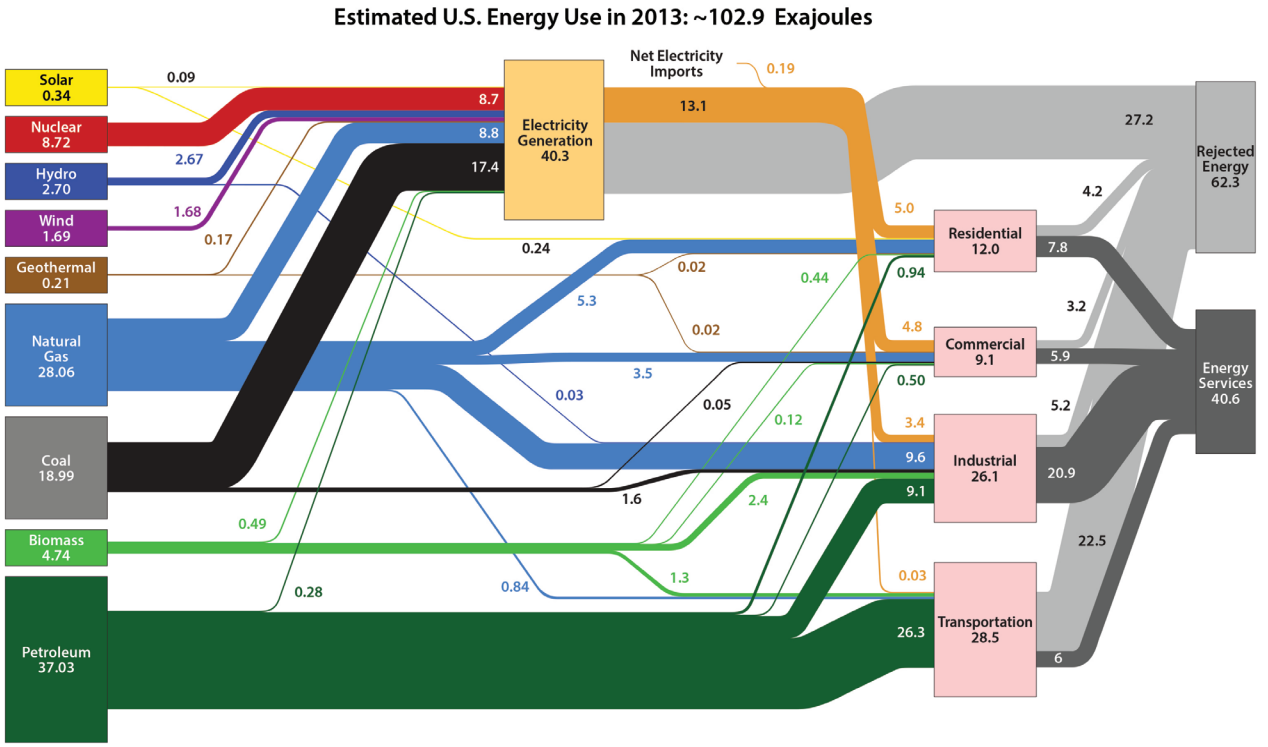
According to IEA (2017a), total North American energy use for transportation exceeded 30 EJ in 2013. The U.S. transportation sector consumed around 28.5 EJ of this energy, 91.6% of which was from petroleum, 3.3% from natural gas, and 5.0% from biofuels (EIA 2017b; IEA 2016d). Canada's transportation sector consumed approximately 2.6 EJ (IEA 2017a), and about 94% of transportation fuels were petroleum products and 5.3% natural gas (CESAR 2018). Mexico's transportation sector consumed about 2.1 EJ in 2013, equal to 48% of total national energy consumption, with almost all of it from motor vehicles (Secretaría de Energía de México 2016).

In 2013, North American transportation CO_2e emissions exceeded 2.15 Pg CO_2e (585 Tg C). The U.S. transportation sector alone contributed approximately 1.80 Pg CO_2e (499 Tg C) in 2013, or more than 28% of the nation's total greenhouse gas (GHG) emissions (U.S. EPA 2016). During the same year, Canadian emissions exceeded 0.2 Pg CO_2e (54 Tg C), accounting for about 24% of the country's total emissions (ECCC 2017b). In Mexico, emissions from road vehicles in 2013 dominated transportation emissions, with vehicles emitting 0.153 Pg CO_2e (41.7 Tg C), equal to 31% of the net national total. Total Mexican transportation-sector emissions were 0.174 Pg CO_2e (47.5 Tg C), equal to 34% of net national emissions for that year (SEMARNAT-INECC 2016). Mexican transportation energy use and emissions are expected to rise dramatically over the coming decades (IEA 2015b).

The North American transportation system is clearly large, complex, and highly integrated with regional economic and social development. Because of transportation's importance as an energy sector and its significant effects—including economic costs, risks of dependence on oil, environmental impacts on air quality and health, and carbon emissions—advancing clean (i.e., low-emission) and efficient vehicle systems and technologies could have extensive impacts across societies. A range of technologies at various stages of research and development offer the potential to increase energy efficiency and mitigate impacts, including reducing contributions to the carbon cycle. Key technologies for light- and heavy-duty vehicles include 1) low-temperature combustion engines; 2) alternative fuels and lubricants; 3) advanced light-weight, high-strength materials for vehicle body systems; 4) improved batteries and electric drives; 5) lower-cost and more durable fuel cells; and 6) more efficient onboard hydrogen storage. Beyond vehicle improvements, a variety of existing or developing technologies can be leveraged to meet projected increases in North American air, water, off-highway, and rail transportation. Improved technologies could reduce the energy intensity of the entire transportation system, resulting in significant reductions in carbon emissions (U.S. DOE 2015b).

Summary

Given the complexity of the energy system, comprehending the size of relative energy flows from primary supply to end use is difficult. Sankey diagrams, developed by Matthew Henry Sankey in 1898, demonstrate flows to and from individual system components via the width of the bands, which, in this case, are directly proportional to energy production, usage, and losses. This visual account helps to summarize not only how the system works, but where efforts to change operations may be most effective. Figure 3.3, p. 125, presents Sankey diagrams for U.S. energy use and CO_2e emissions in 2013. On the left side of the diagrams are the primary energy supply sources, and on the right side are the energy end uses with electricity generation in the middle. A few immediately notable points are reviewed in this chapter: 1) renewables make up a small share of energy flows (although that share is growing); 2) most coal fuel is used for electricity generation (although the band width is decreasing); 3) natural gas fuel is split largely between electricity generation and residential, commercial, and industrial energy uses (all of which are increasing); 4) most petroleum fuel is used for transportation with some for industry; 5) values for rejected or unused energy are larger than those for energy services (suggesting a potential for enhanced efficiency); and 6) the electricity generation and transportation sectors are the largest sources of CO_2e emissions, followed by industry.



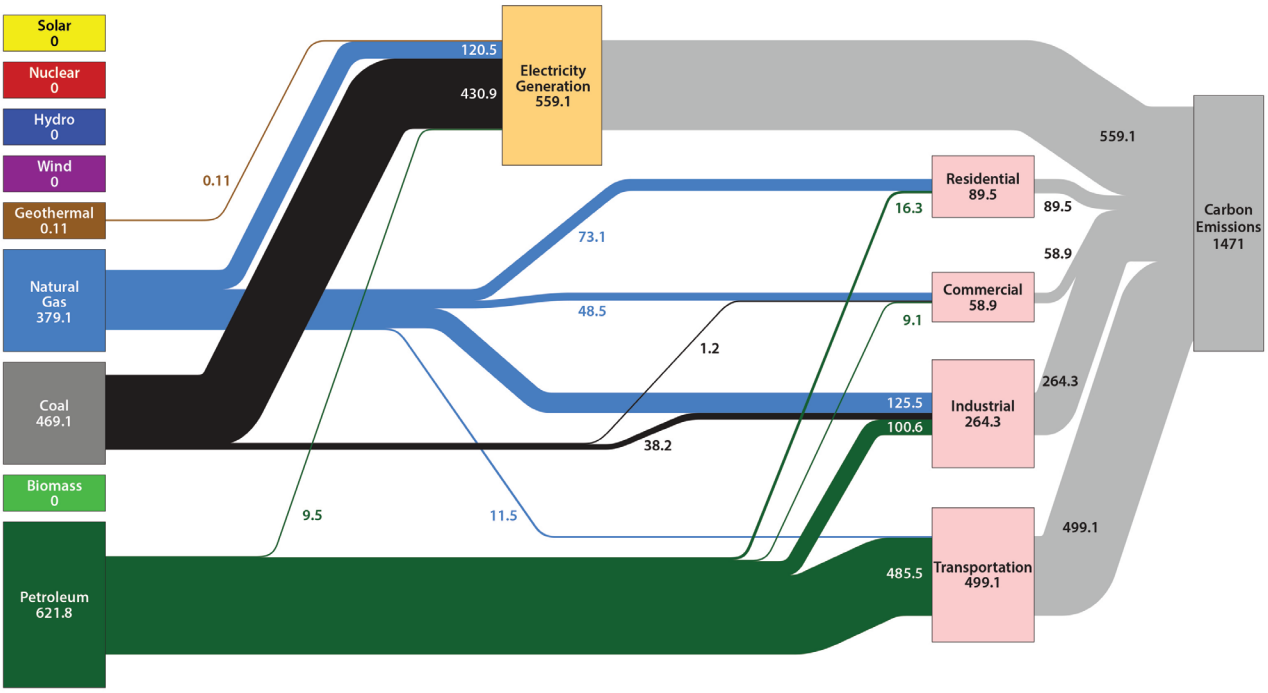


Figure 3.3. Flows of U.S. Energy Use and Carbon Emissions, 2013. Key: Tg C, teragrams of carbon. [Figure source: Adapted from Lawrence Livermore National Laboratory (2018), flowcharts.llnl.gov/commodities/energy.]

3.3.3 Carbon Sink Technologies

Carbon sequestration, the process of capturing and storing atmospheric carbon, has been proposed as a way to slow the atmospheric and marine accumulation of GHGs that are released by burning fossil fuels. One set of increasingly popular sequestration technologies comprises carbon capture and storage (CCS) and carbon dioxide utilization (CDU). CCS captures CO_2 emissions produced from the use of fossil fuels in electricity generation and industrial processes, thus preventing them from entering the atmosphere after their subsequent storage in deep geological formations. The CCS process also can be used to take carbon directly out of the atmosphere, typically including CO_2 capture, transport, and storage in depleted oil and gas fields or saline aquifer formations.

North American CCS achieved an important milestone in 2014, with Canada's Boundary Dam Unit 3, with a net capacity of 120 megawatts (MW) becoming the first commercial power plant to come online with CO_2 capture. The 38 large-scale CCS projects either in operation or under construction have a collective CO_2 capture capacity of about 60 Tg per year, while the 21 in operation now capture 40 Tg CO_2 per year (Global CCS Institute 2016). The present pace of progress in CCS deployment, however, falls short of that needed to achieve average global warming of 2°C (IEA 2015a). Constraints include financial and technological challenges to overcome low efficiency and energy losses, as well as a lack of public acceptance (Haszeldine 2009; Smit et al., 2014). Regardless, CCS technologies often are included in scenarios as an increasingly effective way to remove CO_2 from the atmosphere (see Section 3.8, p. 154). One particularly important application is bioenergy with carbon capture and storage (BECCS), which has been indicated as a key technology for reaching low-CO_2e atmospheric targets (Fischer et al., 2007).

Carbon dioxide usage includes direct and indirect aspects. The most successful direct use has been in enhanced oil recovery (EOR) and enhanced coalbed methane (ECBM; CH_4) recovery, in which CO_2 is injected into oil or natural gas fields to enhance the resource recovery rate (NETL 2010, 2017). Indirect CDU technologies involve the reuse of CO_2 emissions from power plants or industrial processes to produce value-added products. Indirect CDU includes using chemical, biochemical, and biotechnological means to create energy fuel, polymers, and carbonates from the CO_2. Overcoming technical, economic, and strategic challenges remains an issue before this option becomes viable (Al-Mamoori et al., 2017; Song 2006).

3.4 Indicators, Trends, and Feedbacks

This section identifies the major trends over the past 10 years that have shaped North American energy system dynamics and current understanding of the relationship between the energy system and the carbon cycle (see Table 3.3, p. 127). Importantly, the North American energy system is undergoing a transformation. How the system ultimately will emerge is unclear, but the outlines of change are already evident.

At least five major trends and a number of associated indicators demonstrate a shift from patterns described in SOCCR1. These new trends are 1) a decrease in energy use (e.g., reduced oil use and stable or reduced electricity demand) and total CO_2e emissions since 2007, 2) an energy transition based on increased shares of natural gas in North America's primary fuel mix and in electricity generation, 3) increased renewable energy inputs into the electrical system, 4) increased concern about aging energy-related infrastructure, and 5) new understanding that has altered thinking on the role of biofuels and natural gas in the carbon cycle. Each of these dynamics is described herein, first for the region and then for each economy within the region. The descriptions include historical and nationally comparable data from 2004 to 2013, with more recent information for some energy subsectors in individual nations. The section ends with a discussion of feedbacks related to energy use and energy-related CO_2e emissions that are immediately important or may become important for regional energy systems in the near future.

Table 3.3. Five Major Trends, Indicators, Drivers, and Impacts on the Carbon Cycle

Trends	Indicators	Drivers	Impacts on Carbon Cycle
Decline in energy use and carbon dioxide equivalent (CO_2e)[a] emissions	Decrease in total energy use with declines in demand for oil products and a slowed rate of increase in electricity demand	Economic recession, lower carbon intensities of fuels due to switching to natural gas and increases in renewables, lower energy intensities due to efficient new technologies, governmental policies, and ongoing structural changes leading to lower energy intensity	Lower emissions
Natural gas transition	Larger primary energy contribution from natural gas, increase in natural gas reserves, expansion of fracking, fuel switching in electricity generation and industry	New technologies, policies, and market forces (prices)	Lower emissions (potentially) offset by methane leakage
Increased renewable energy	Larger number and capacity of wind and solar power–generation plants, resulting in larger contributions of these sources to electricity generation	New technologies, governmental policies, and market forces (prices)	Lower emissions
Aging infrastructure	Age of infrastructure, higher costs of replacement, and increasing examples of infrastructure failure	Lack of public financing and political action	Potentially higher emissions
New understanding of biofuels and fugitive (e.g., leaked) natural gas emissions	Increasing number of studies demonstrating land-use emissions from biofuel production and potentially large unaccounted-for emissions levels from natural gas extraction, transmission, and distribution	Better understanding of 1) fuel life cycle and 2) indirect impacts of fuel production, transmission, and distribution	Revised estimates of emissions (impact may be positive or negative)

Notes

a) Carbon dioxide equivalent (CO_2e): Amount of CO_2 that would produce the same effect on the radiative balance of Earth's climate system as another greenhouse gas, such as methane (CH_4) or nitrous oxide (N_2O), on a 100-year timescale. For comparison to units of carbon, each kg CO_2e is equivalent to 0.273 kg C (0.273 = 1/3.67). See Box P.2, p. 12, in the Preface for details.

3.4.1 Decline in Energy Use and CO_2e Emissions

North American energy demand has decreased from 2004 to 2013 at about 1% annually. The greatest decreases occurred from 2007 to 2009 (see Figure 3.4, p. 128). In 2004, North American total primary energy demand was about 127 EJ, rising to 128 EJ in 2007. After that, energy consumption decreased to a low of 120 EJ in 2009. Over the past 4 years, average annual consumption has equaled about 124 EJ. The largest decreases in energy were experienced by the United States, which fell from a high of 107 EJ in 2007 to 103 EJ in 2013. However, energy consumption in both Canada and Mexico slightly increased. For example, Canada's primary energy use was 13.6 EJ in 2007 and 14.9 EJ in 2013. Mexico's energy use was 7.1 EJ in 2007 and 7.7 EJ in 2013 (EIA 2016c).

An important indicator of this trend has been reductions in oil consumption, particularly refined

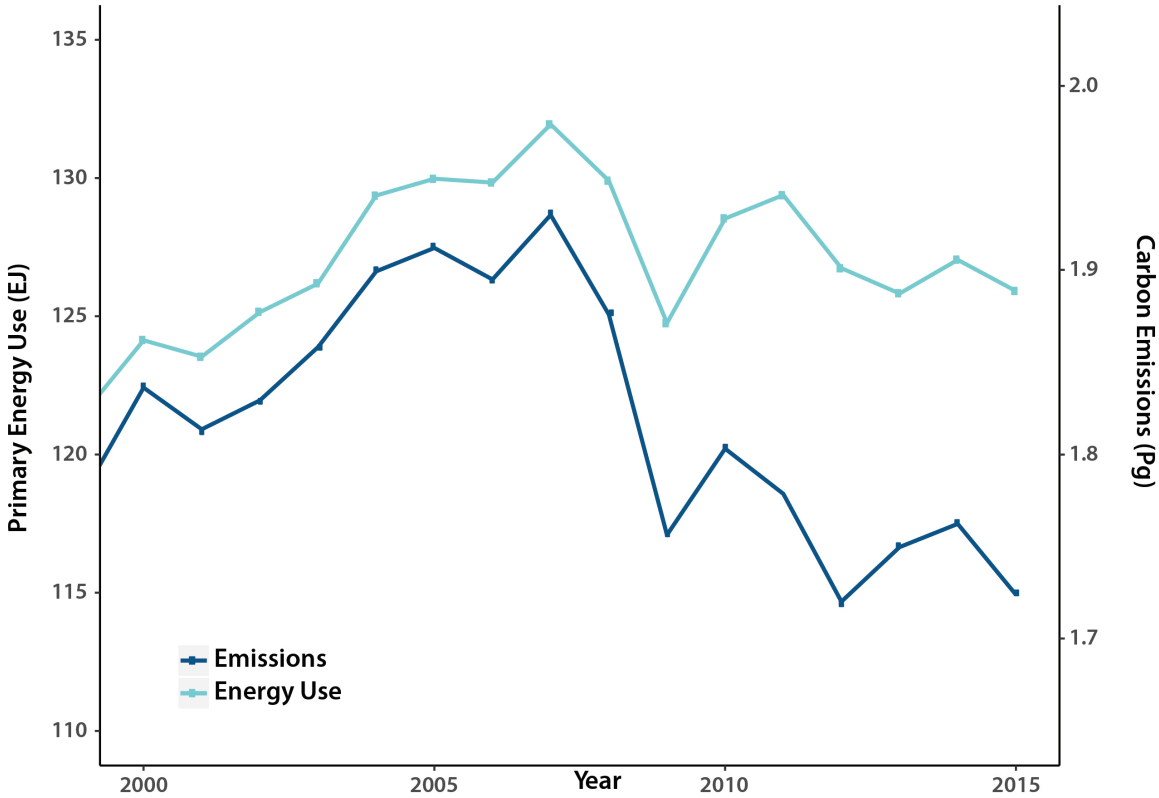


Figure 3.4. North American Primary Energy Consumption and Carbon Emissions, 2000 to 2015. Energy use in exajoules (EJ); carbon emissions in petagrams (Pg). [Data source: EIA 2017i.]

products. North American use of petroleum declined from 51.4 EJ in 2004 to 46.2 EJ in 2013. The trend was not monotonic, however. Between 2004 and 2007 consumption was stable before declining thereafter. The year with lowest consumption (45.6 EJ) was 2012. Similar to the trend in overall energy use among North American countries are decreases in oil consumption, which were experienced largely in the United States, while consumption in Canada increased from 4.6 EJ to 5.0 EJ and remained about the same in Mexico at 4.3 EJ to 4.2 EJ from 2004 to 2013 (EIA 2016c).

Total petroleum consumption per capita in the United States recently shifted as well. From 1990 to 2006, consumption was in the range of 142 GJ per capita. Since that time, petroleum consumption has dropped, reaching a low in 2012 of 116 GJ per capita. In 2013, consumption was 117 GJ per capita (EIA 2016b; Hobbs and Stoops 2002; U.S. Census 2016). Motor gasoline consumption per capita in the United States followed a similar trend. In 2006, gasoline consumption per capita was 63.2 GJ, but it fell thereafter, reaching a low of 56.1 GJ in 2012. Consumption levels were 56.5 GJ per capita in 2013 (EIA 2016b).

Another important indicator is the slow growth in U.S. grid–based electricity demand, which is now growing at its lowest level in decades. Since 2006, increases in electricity generation have slowed or stabilized (EIA 2016c, 2016f). Prior to 2007, electricity demand was on an increasing trend. For example, electricity generation was about 8.2 EJ in 1980; by 2007, it had reached 15 EJ. Electricity generation has since remained below 14.9 EJ and was 14.6 EJ in 2013 (including net imports). The trend has been similar in Canada where total electricity

demand has hovered just below 1.8 EJ for the past 10 years. There are variations across states and provinces within the United States and Canada, but the overall trend in these large markets has resulted in flat or slightly declining demand for electricity. The U.S. and Canadian slowdown in electricity demand is characteristic of a trend observed in other mature, industrial economies where structural change, energy end-use market saturation, and technological efficiency improvements are offsetting upward pressure from growth in population, economic output, and energy service demand. In Mexico, because the factors pushing electricity demand growth have continued to prevail over efficiency gains and other moderating influences, total electricity generation has continued to grow, from 0.79 EJ in 2004 to more than 1.01 EJ in 2013, a 27% increase.

North American total energy-related carbon emissions from 2007 to 2013 have declined at a rate of just under 2% per year, translating into an annual reduction of about 0.11 Pg CO_2e (30.6 Tg C). According to the U.S. Environmental Protection Agency (U.S. EPA; U.S. EPA 2016), U.S. energy-related fossil fuel emissions peaked in 2007 at 5.8 Pg CO_2e (1.58 Pg C) and subsequently dropped to 5.16 Pg CO_2e (1.47 Pg C) in 2013. Total emissions in Canada declined over the past few years. Between 2005 and 2013, its total GHG emissions decreased by 3.1%, falling from about 0.74 to 0.72 Pg CO_2e (201 to 197 Tg C; ECCC 2017b). Mexico, however, experienced an increase in emissions, from 0.4 Pg CO_2e (109 Tg C) in 2007 to 0.45 Pg CO_2e (122.73 Tg C) in 2013 (IEA 2016d). Given the relatively small increases in Mexico compared with the declines in the United States and Canada, overall emissions in North America declined.

3.4.2 North American Natural Gas Energy Transition

A natural gas boom is driving a transition in the North American energy system (EIA 2016d). This boom increased North American dry gas production from 28.5 EJ in 2004 to approximately 33.9 EJ in 2014, a 2% average annual increase over this period. Natural gas production from shale gas now makes up about half the U.S. total dry natural gas production. Canada's dry natural gas production decreased by more than 21% during this period. In Mexico, during the same period, dry gas production increased by 24% to 1.8 EJ (EIA 2016b). For North America, the natural gas share of total primary energy and electricity generation has climbed dramatically since 2005 from 24% and 14%, respectively, to about 30% for each in 2015 (see Figure 3.5, p. 130).

Resources in low-permeability rock formations have supplemented U.S. natural gas reserves. For natural gas, formations include the Barnett, Fayetteville, Haynesville, Woodford, Bakken, Eagle Ford, and Marcellus shales. Recent access through horizontal drilling and hydraulic fracturing (i.e., "fracking") has boosted both natural gas and oil production dramatically. In 2016, hydraulic fracturing accounted for about 48% of current U.S. crude oil production (EIA 2017d, 2017l) and 60% of total natural gas production.

Globally, unconventional gas production has the longest history in the United States. Commercial production of coalbed CH_4 began in the 1980s, expanded in the 1990s, and leveled off in recent years. Shale gas production has occurred for several decades but started to expand rapidly only in the mid-2000s, growing at more than 45% per year from 2005 to 2010. The United States, Canada, China, and Argentina are the only four countries currently producing commercial shale gas, with U.S. and Canadian production accounting for virtually all of the global supply. North American success in shale gas production holds the prospect of a large-scale unconventional gas industry emerging in other parts of the world where sizeable resources are known to exist. Mexico and Algeria expect to develop operations after 2030.

In the United States, natural gas demand for electric power generation has increased dramatically in recent years. In 2002, the electric power industry used 16.8 petajoules (PJ) of natural gas a day, or 6.07 EJ a year, accounting for approximately

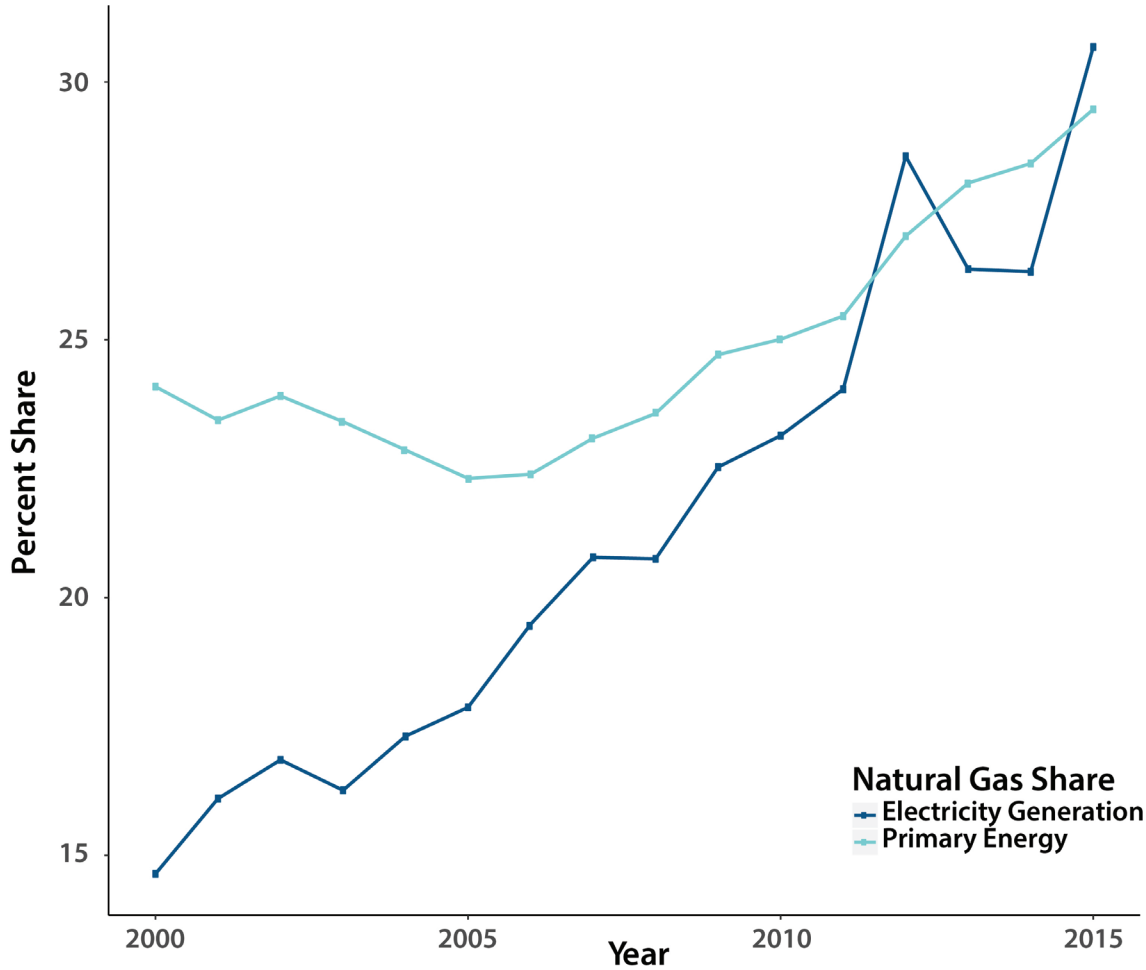


Figure 3.5. North American Natural Gas Share of Primary Energy and Electricity Generation, 2000 to 2015. [Data sources: EIA 2017i and IEA 2017b]

24.6% of all U.S. natural gas usage. Electric power industry demand for natural gas grew to 19.7 PJ a day in 2008 and then rapidly increased thereafter. By 2013, the electric power industry was using more than 24.3 PJ of natural gas a day; by 2015, levels had reached 28.6 PJ a day (EIA 2016e). Prior to 2016, natural gas had long been the second-most-prevalent fuel for electricity generation behind coal. However, in that year, natural gas–fired power plants accounted for about 34% of U.S. electricity generation, followed by coal (30%), nuclear (19%), and renewables (15%) (EIA 2016c). The electric power industry's use of natural gas now exceeds that of the industrial sector (EIA 2012b).

In 2003, Canadian natural gas production made up only 6% of total net electricity generation, using approximately 1.08 PJ of natural gas per day. By 2014, 8.5% of the country's electricity supply was generated from natural gas at a rate of about 1.3 PJ per day (Natural Resources Canada 2016c). Mexico increased natural gas production from 2009 to 2013, and the country has doubled imports from the United States through pipelines. According to Mexico's national energy

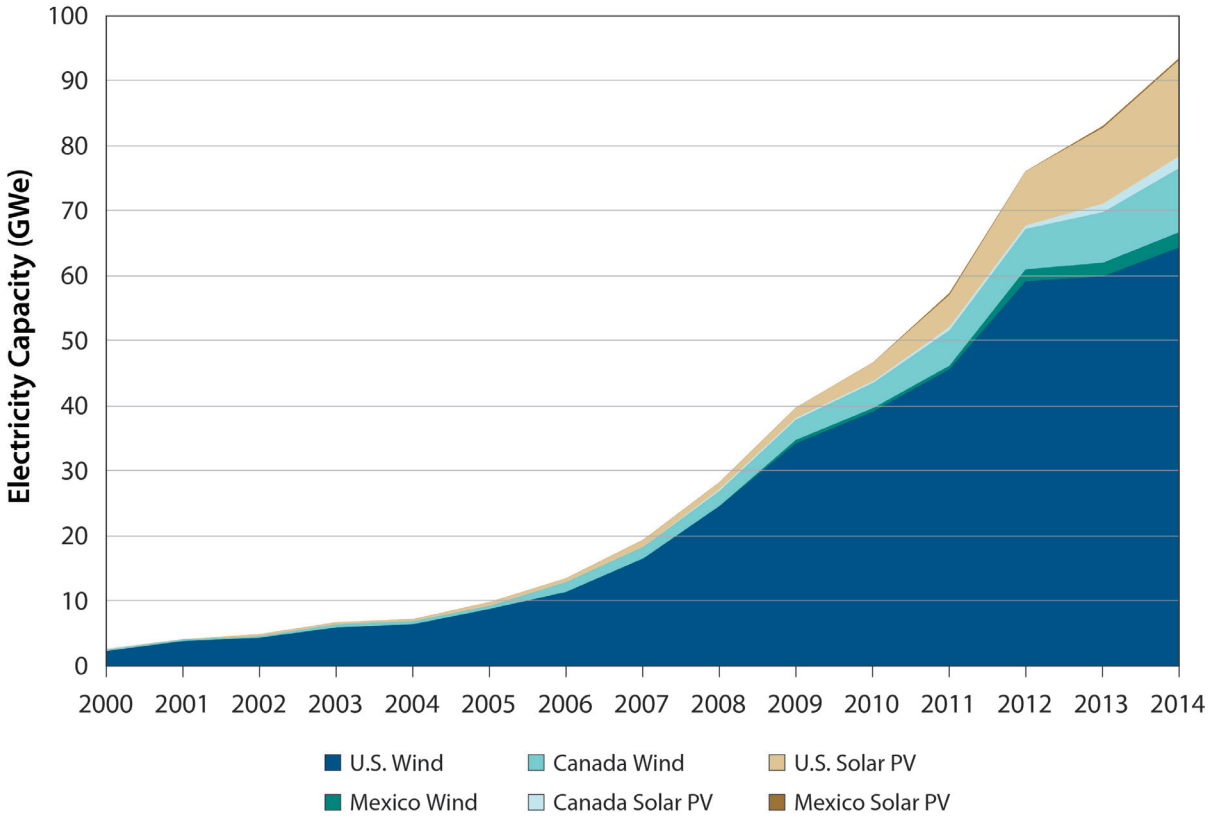


Figure 3.6. North American Wind and Solar Net Capacity, 2000 to 2014. Key: GWe, gigawatt electrical; PV, photovoltaic. [Data source: IEA 2018.]

ministry, SENER, natural gas is Mexico's largest source of electricity generation, accounting for 54% of the country's generation in 2015, up from 34% in 2005 (EIA 2017c). SENER projects that natural gas–fired capacity will account for 24.9 GW of total capacity additions from 2016 to 2029 (SENER 2015). The rest of Mexico's projected capacity additions consist of renewables (20.4 GW) and nuclear (3.9 GW) (EIA 2017c).

3.4.3 Increase in Renewable Energy

Globally, renewable-based power generation capacity increased by an estimated 165 GW in 2016, accounting for more than 66% of the additions to world power generation capacity for the year (IEA 2017d). Of the increased renewable generation capacity, 45% was from PV solar, 32% from wind, and 20% from hydropower. The growth in solar capacity was attributed largely to Chinese increases in solar installations, while the recent fall of wind installation capacity (20% from 2015) was due to cuts in China (IEA 2017d).

North America is increasing its renewable power capacity (see Figure 3.6, this page). For electricity, the contribution of nonhydropower renewables (e.g., wind, solar, and biomass) to total power generation grew from 2.4% in 2004 to 6.1% in 2013, translating into a 10.6% annual average increase, or an additional 220 PJ of renewable energy into the North American electrical system annually. In 2016, about 10% of total U.S. energy use was from renewable sources (EIA 2018a). According to IEA

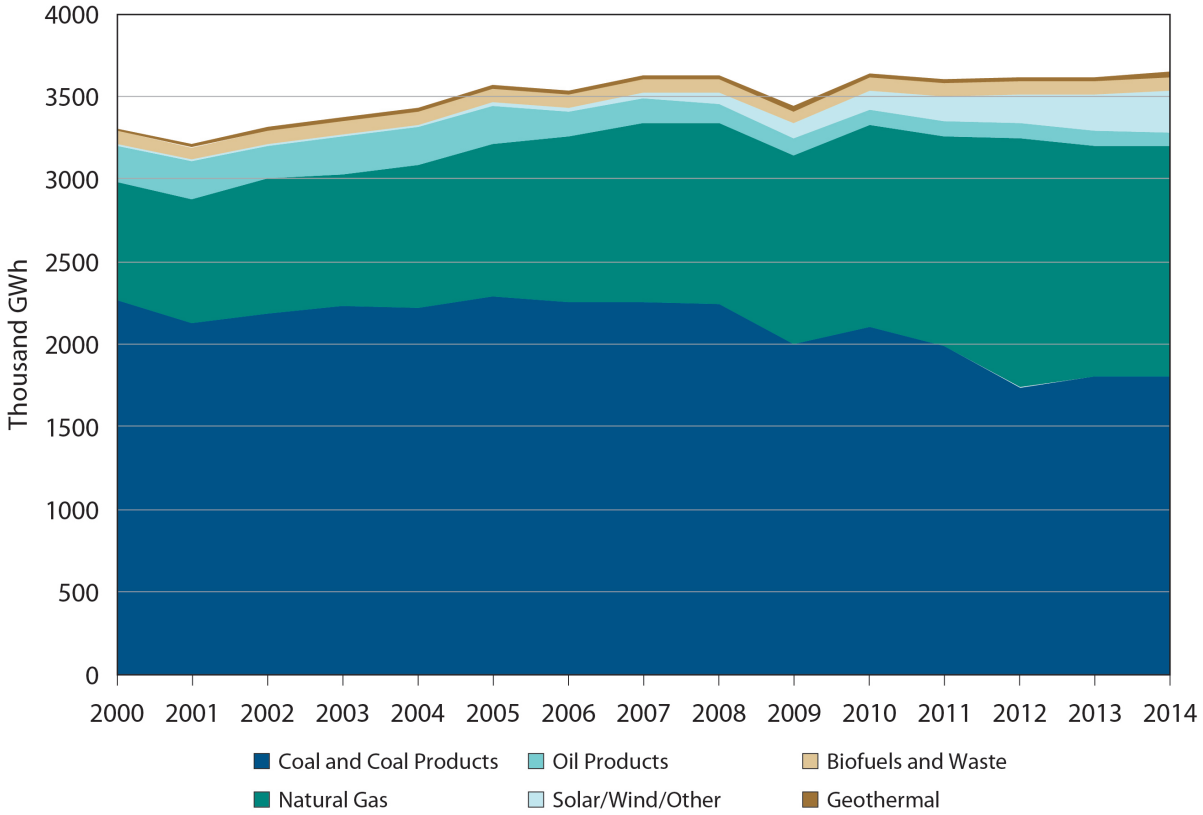


Figure 3.7. Renewable and Fossil Fuel Electricity Production in North America, 2000 to 2014. Key: GWh, gigawatt hours. [Data source: IEA 2017a.]

(2017d), North America is the world's second largest growth market for new renewable capacity, led by the United States.

Although renewables are an increasingly important component of total generation capacity, renewable energy's share of total primary and secondary energy supplies remains low (see Figure 3.7, this page).[10] For example, in 2013 the total supply of nonhydropower renewable energy (e.g., geothermal, wind, solar, tidal, wave, fuel cells, and biomass) for electricity generation in North America was 3.25 EJ. Yet, these sources together accounted for approximately 6.1% of total electricity generation, while hydropower accounted for 13.7%, nuclear 18%, and fossil fuels more than 62% (EIA 2016f, 2016g).

Nevertheless, renewable energy continues to make strides across North America. In the United States, solar electricity generation increased by 31 PJ in 2014—from 32.4 PJ to 63.4 PJ—or a 96% increase from the previous year. U.S. wind generation increased by 8%, from 604.1 PJ to 654.2 PJ (EIA 2016g). In 2015, wind's share of total U.S. electricity generation reached approximately 655 PJ, accounting for 4.7% of net electric power generation

[10] Only since recently has the U.S. Department of Energy's Energy Information Administration (EIA) officially collected data on small-scale renewables (<1 megawatt [MW] of generation capacity), and only since 2017 have these values been added to the *Short-Term Energy Outlook* reports (EIA 2017a). The amount of small-scale renewable energy, however, is considerable. For example, EIA estimates for 2016 show that about 37% of total annual photovoltaic solar generation is from small-scale generators having a capacity less than 1 MW (EIA 2017m). Hence, the figures presented here may underestimate total renewable energy electricity generation.

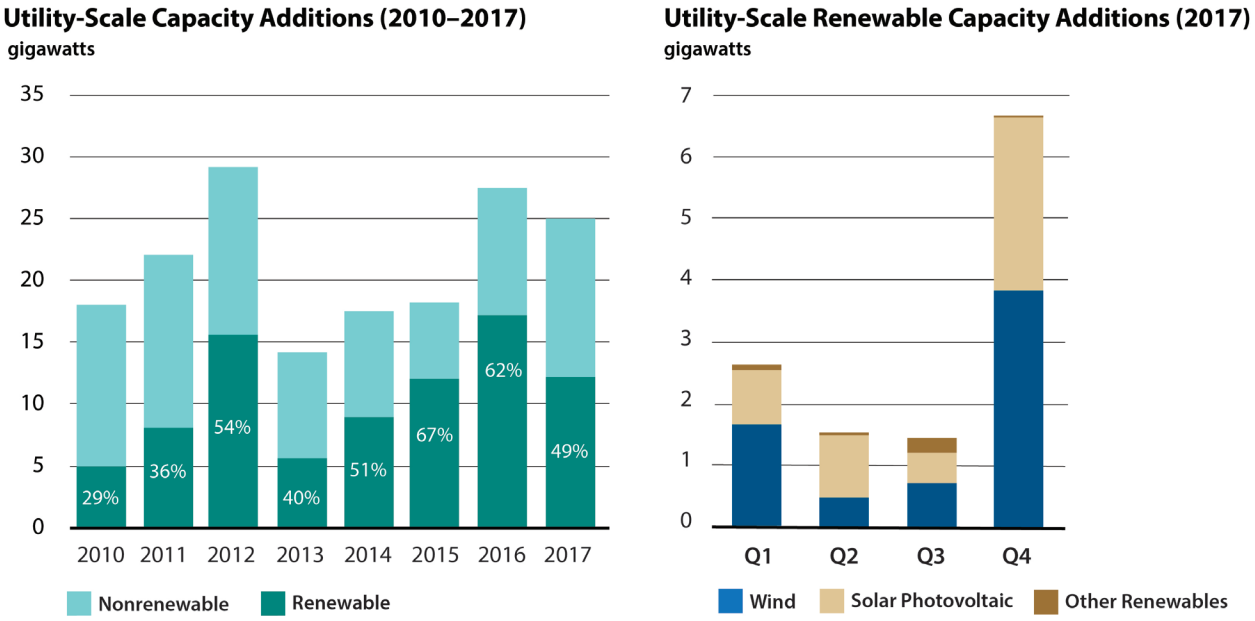


Figure 3.8. Renewable Generation Capacity (2010 to 2017) and Utility-Scale Additions, 2017. [Figure source: Redrawn from EIA 2018b.]

(EIA 2017l). By 2016, about 8.4% of electricity generation was from nonhydropower renewable sources (EIA 2017a). During 2016, renewable generation capacity accounted for most of the electricity capacity additions (EIA 2017a; see Figure 3.8, this page), and nearly half of utility-scale capacity in 2017 (EIA 2018b). By 2017, wind and solar renewable shares reached 10% of electricity generation for the first time (EIA 2017a). From 2008 to 2016, U.S. wind generation increased threefold, and solar generation expanded 40-fold (Houser et al., 2017). California and, most recently, North Carolina have added a significant portion of the increased U.S. solar capacity. Other states using policies to encourage PV installations include Nevada, Texas, Arizona, Georgia, and New Jersey (EIA 2016f, 2016g; World Energy Council 2016a). Wind development has advanced in Iowa, South Dakota, Kansas, Oklahoma, North Dakota, Minnesota, Idaho, Vermont, Colorado, Oregon, and Maine, where it exceeded 10% of total electricity generation in 2015 (EIA 2016h). Other states with significant wind programs include Texas and New Mexico (for a discussion of carbon-related subnational policies, see Section 3.7, p. 149).

Canada also has built new renewable power capacity, most of which comes from hydroelectric sources. In fact, the country is the second largest producer of hydroelectricity in the world, generating more than 1.36 EJ in 2014, or 59% of total national supply. Hydropower remains Canada's main source of electricity supply, but nonhydropower renewable electricity generation grew from 34.2 PJ in 2002 to 90 PJ in 2013, a more than 1.5-fold increase. By 2014, Canada had 9.6 GW of installed wind power capacity (Natural Resources Canada 2016c) and added another 1.55 GW of wind-generating capacity in 2015 alone, which now supplies about 5% of the country's electricity demand (World Energy Council 2016a). Canada also has significant bioenergy electrical capacity, exceeding 2 GW in 2014 (Natural Resources Canada 2016a).

In Mexico, the largest source of renewable power generation is hydropower. Hydroelectricity supplied about 10% of the nation's electricity in 2015 (EIA 2015a). Mexico has also increased its nonhydropower renewable energy but at a slower rate than that of the United States or Canada. In 2002,

the country's nonhydropower renewable energy generation was approximately 28.4 PJ and increased to 39.6 PJ in 2013 (EIA 2016d). Nonhydropower renewables represented 3% of Mexico's electricity generation in 2013. Mexico also has 980 MW of geothermal capacity, making the country fifth in terms of global geothermal capacity. In 2015, 100 MW of geothermal projects are expected to supplement the decreased power generation at the 645-MW Cerro Pietro Geothermal field in Baja California, the key component of Mexican geothermal generation. Solar power has received significant attention in northern Mexico, where the first large-scale solar power project, Aura Solar I, began operations in 2013. This project increases Mexican solar capacity by 30 MW. Several wind projects under development in Baja California and in southern Mexico aim to boost Mexico's wind-generation capacity from 2 to 12 GW by 2020. Mexico is hoping to achieve this goal by encouraging US$14 billion in investment between 2015 and 2018. In 2016, renewable capacity additions reached 0.7 GW, led by onshore wind (0.45 GW) and solar PV (0.2 GW). These additions were mostly from power purchase contracts with the Federal Electricity Commission before implementation of energy reform (IEA 2017d). Much of the current wind-generation capacity is in Oaxaca, where the Isthmus of Tehuantepec has especially favorable wind resources and has been a focus of governmental efforts to increase wind capacity. From 2010 to 2013, the Oaxaca region experienced an increase of nearly 667% in wind-generation capacity with the addition of five major projects (Oaxaca I, II, III, and IV and La Venta III), bringing the region's total wind-generation capacity to 1.75 GW (EIA 2015a). Mexico's first power auction (see Section 3.3.2, p. 118) generated a further 1.7-GW commitment to solar and wind generation, which also may affect the country's future fuel mix.

From 2003 to 2012, North American consumption of biofuels (i.e., liquid fuels such as ethanol and biodiesel derived from renewable plant sources) increased by almost 20% annually, and biofuels now constitute an important component of the continent's fuel mix. In the United States, almost all gasoline contains 10% blended ethanol (E10), the maximum level approved for use in all cars and light trucks, although higher levels could be used with appropriate adjustments. The amount of fuel ethanol added to motor gasoline consumed for transportation in the United States increased from about 1.4 billion gallons in 1995 to about 14.4 billion gallons in 2016. Biodiesel consumption increased from 10 million gallons in 2001 to about 2.1 billion gallons in 2016 (EIA 2017b). Canada's biofuel blend mandate is 5% renewable content (ethanol) in gasoline and 2% in distillate (diesel). Provincial blend mandates, however, reach as high as 8.5% for ethanol in Manitoba. Canada imports close to 20% of its domestic fuel ethanol consumption and nearly all of that from the United States (USDA Foreign Agricultural Service GAIN 2015). In 2016, Mexico released draft standard specifications for biofuels, including a proposed 5.8% ethanol blend nationwide. However, the final regulation was limited to the three largest major metropolitan areas (Mexico City, Guadalajara, and Monterrey), which represent one-third of Mexico's population (U.S. DOC 2016).

3.4.4 Growing Concern over Aging Energy Infrastructure

North America is poised for significant investment to meet the challenges of its aging transportation and energy infrastructures, including energy generation, transmission, distribution, and storage systems. A number of studies have found that energy systems in the United States urgently need upgrading (ASCE 2013; U.S. DOE 2015a). In 2008, the Edison Electric Institute estimated that by 2030 the U.S. electric utility industry would need to invest $1.5 trillion to $2.0 trillion in infrastructure (Edison Electric Institute 2008). Harris Williams & Co. (2014) suggest that an estimated 70% of U.S. transformers are more than 25 years old, 60% of distribution poles are 30 to 50 years old (relative to useful lives of 20 and 50 years, respectively), and 70% of transmission lines are also approaching the end of their useful lives of 25 years or older. In Canada, infrastructure underinvestment since the 1980s has put a strain on existing facilities (Gaudreault and Lemire 2009). The World Economic

Forum's Global Competitiveness Report for 2012 to 2013 noted that energy infrastructure is a main area of needed improvement in Mexico (Goebel and Schwandt 2013; Schwab and Sala-i-Martín 2012).

Infrastructure needs extend to electricity-generation plants. In the United States, nearly 18 GW of generating capacity retired in 2015, 80% of which is coal-fired generation (EIA 2016l, 2018c). Although current nuclear-powered electricity generation in North America is stable, there are significant retirements slated in the midterm future. The United States currently has around 99 nuclear reactors in full operation, five under construction, 25 in the planning and permitting stage, and 32 in permanent shutdown or retirement. However, there are five fewer generators operating now than at the end of 2012, corresponding to a decrease in about 3 GW of nuclear capacity. Generation has remained relatively stable because output of the operating plants has been increasing. In 2014, U.S. nuclear power accounted for 8.76 EJ, approximately 8.5% of national total primary energy. Currently, the United States accounts for more than 30% of the worldwide nuclear generation of electricity (World Energy Council 2016a). For the entire continent, nuclear power generation since 2002 has been largely flat, accounting for about 850 to 900 billion kilowatt hours (kWh; 3.04 to 3.24 EJ; EIA 2016c). Nuclear plants continue to be decommissioned, but their potential replacement by new nuclear technologies, coal- or gas-fired thermoelectric plants, or renewable resources is unclear (see Box 3.2, Potential for Nuclear Power in North America, p. 120).

ICF, on behalf of the Interstate Natural Gas Association of America (INGAA) Foundation, recently published a report estimating that necessary midstream energy infrastructure investments for the United States and Canada would be between $22.5 billion and $30 billion per year, or approximately $546 billion (US$ 2015) over the 20-year period from 2015 to 2035 (INGAA 2016). These investments include mainline pipelines; laterals; processing plants; gathering lines; compression equipment for gas transmission and gathering lines; and storage for natural gas, natural gas liquids, and oil. Nearly 50% of U.S. gas transmission and gathering pipelines were constructed in the 1950s and 1960s when the interstate pipeline network expanded in response to the thriving post–World War II economy. According to U.S. DOE (2015a), upgrading U.S. natural gas pipelines would cost an estimated US$2.6 billion to US$3.5 billion per year from 2015 to 2035, depending on the overall level of natural gas demand. Replacing cast iron and bare steel pipes in gas distribution systems would cost an estimated US$270 billion (U.S. DOE 2015a).

Studies suggest that infrastructure improvements could lower carbon emissions through reducing leaks from water supplies and natural gas transmissions, improved power plant efficiencies, increased connectivity throughout cities, improved transit, and upgraded transmission and distribution infrastructure, including biofuel refineries, liquid fuel pipelines, and vehicles that transport energy directly or indirectly (Barrett et al., 2014; U.S. DOE 2015a; World Resources Institute 2016).

3.4.5 New Understanding of Biofuel and Natural Gas Contributions to Carbon Cycle Dynamics

Biofuel mandates at both the U.S. federal and state levels target transportation fuels (Adler et al., 2012). Quantifying the degree to which the use of this energy source contributes to the global carbon cycle, however, requires a thorough accounting of both the upstream impacts of the various materials and activities required to produce the finished fuel and the emissions at the point of fuel use.

Accounting for the full life cycle of carbon emissions related to energy production and use is particularly challenging. An example is the case of biofuels, where impacts spill over into the agricultural sector via nonpoint source trace gas emissions from—and changes in carbon storage within—the agroecosystems from which feedstock biomass is sourced. Thus, those climate cycle impacts can be examined by supplementing traditional GHG inventories with consequential life cycle assessment studies

that attempt to quantify direct impacts all along the supply chain, as well as indirect effects that could erode the direct GHG mitigation benefits of an agricultural system (Brander et al., 2009; Plevin et al., 2014). Nearly four decades have elapsed since scientists first analyzed fossil energy expenditures associated with corn ethanol production to determine whether it represents a viable strategy to improve domestic energy security (Silva et al., 1978), and such energy use and associated GHG emissions are increasingly quantified with greater certainty (Farrell et al., 2006).

Understanding of other biofuel life cycle GHG emissions impacts has expanded greatly over the last decade. The research community now widely recognizes that feedstock production often results in changes in above- and belowground carbon storage and emissions of nitrous oxide (N_2O) and CH_4 relative to current or alternate land management (Robertson et al., 2011). Such biogenic impacts vary widely depending on the crop cultivated, regional climate, and site-level factors including soil properties and land-use history, and they require spatially explicit models for accurate assessment (Field et al., 2016; Sheehan et al., 2003; Thomas et al., 2013). Researchers also have explored whether conversion of limited arable land to bioenergy crops might increase agricultural commodity prices and elicit land-use changes in other regions, resulting in a leakage effect (Searchinger et al., 2008), though estimates of the magnitude of leakage have been lowered sharply over time (Wang et al., 2011; Zilberman 2017). The leakage effect occurs when GHG emissions increase in one location as a result of decreases in another.[11] Such effects might even run in the opposite direction in some scenarios; studies indicate that increased forest harvesting in response to higher demands for forest biomass is followed by expanding forest area (Galik and Abt 2016; Lubowski et al., 2008). According to U.S. EPA's Science Advisory Board, "Carbon neutrality cannot be assumed for all biomass energy *a priori*. There are circumstances in which biomass is grown, harvested, and combusted in a carbon-neutral fashion, but carbon neutrality is not an appropriate *a priori* assumption; it is a conclusion that should be reached only after considering a particular feedstock's production and consumption cycle. There is considerable heterogeneity in feedstock types, sources, and production methods, and thus net biogenic carbon emissions will vary considerably" (Khanna et al., 2012).

Taken together, these new insights reinforce the importance of accounting for land-use changes in assessing GHG profiles of biomass fuels. Studies have identified a range of sustainable cellulosic feedstock sources that likely could achieve robust GHG benefits via second-generation biofuel production (Tilman et al., 2009) and future "carbon-negative" bioenergy systems, which are predicted to play a significant role in climate stabilization scenarios (Fuss et al., 2014). U.S. EPA's Science Advisory Board emphasizes that significant methodological challenges remain in bioenergy life cycle assessments, particularly with regard to the timing of ecosystem carbon storage changes relative to other life cycle emissions (Khanna et al., 2012).

Life cycle perspectives also have highlighted how "fugitive" CH_4 emissions from natural gas production, transmission, and distribution can erode the GHG savings anticipated from the "natural gas transition" (for a detailed discussion, see Box 3.3, Methane Emissions from Oil and Gas Production, p. 137). A growing body of literature indicates that official CH_4 emissions underestimate true rates in the natural gas supply chain due to leakage (e.g., Brandt et al, 2014; Marchese et al., 2015). Leakage, in this sense, refers to direct emissions loss during production, delivery, and use of natural gas. Leakage

[11] Leakage effects may occur for a number of reasons including 1) when the emissions policy of a political unit (such as a city, state, or country) raises local costs, subsequently giving a trading advantage to emitters from other political units with a more relaxed policy; 2) when production units in higher emissions cost areas move to locations of cheaper costs; or 3) when environmental policies in one political unit add a premium to certain fuels or commodities, with subsequent fall in demand, that is matched by increases in other political units that do not place a premium on those fuels. GHG leakage is typically defined as an increase in CO_2e emissions outside the political unit taking mitigation actions divided by the reduction in emissions within these political units (Barker et al., 2007).

Box 3.3 Methane Emissions from Oil and Gas Production

New extraction technologies recently have made exploitation of unconventional oil and gas reserves, such as tight oil and shale gas, economically feasible, resulting in a rapid and large increase in U.S. oil and gas production over the past decade. Between January 2005 and January 2016, U.S. natural gas gross withdrawals increased by more 38% (EIA 2017g). Until zero-carbon energy achieves greater market share, natural gas is regarded by some as a potential "bridge" fuel since its carbon dioxide (CO_2) emissions are half those from coal per unit of power generated (Alvarez et al., 2012). The new technologies used to extract unconventional reserves, however, have come with a host of related environmental concerns including 1) emissions of harmful pollutants such as ozone precursors and air toxics like benzene, 2) potential pollution of groundwater, and 3) seismic events related to pumping fluid into the ground. Especially in residential and suburban areas, drilling is being met with legal challenges through which the balance between surface and mineral rights is being tested.

Supply-chain leak rates from unconventional oil and gas production must be small for there to be an immediate climate benefit in switching from coal to natural gas, because the global warming potential (GWP) of methane (CH_4) is much higher than that of CO_2 on shorter timescales. The GWP for CH_4 for the 100-year and 20-year time frames ranges from 28 to 34 and 84 to 86, respectively (see Myhre et al., 2013). This suggests that CH_4 traps heat between 28 and 86 times more effectively than CO_2, depending on the analysis time frame. If CH_4 losses are larger than about 1% to 1.5%, the use of compressed natural gas for heavy-duty vehicles has a climate impact exceeding that of diesel fuel used in those vehicles; if CH_4 losses are larger than about 3%, the use of natural gas for electricity production has a climate impact that exceeds that of coal-power electricity production (Alvarez et al., 2012; Myhre et al., 2013; Camuzeaux et al., 2015). Discussed here is some of the considerable body of work since the *First State of the Carbon Cycle Report* (CCSP 2007) on the climate impact of CH_4 leakage from oil and natural gas production.

Many studies have found that emissions inventories consistently underestimate emissions of CH_4 from oil and natural gas production (e.g., Brandt et al., 2014), while other recent studies have suggested lower emissions than the inventories (e.g., Peischl et al., 2016). In the production segment, certain basins have shown lower emissions than would be expected based on national averages included in GHG inventories. Field studies also have shown that there is considerable variation in the CH_4 loss rate among production regions. Karion et al. (2013) found that emissions from the Uintah basin in Utah were about 9% of production. Peischl et al. (2015) found leak rates well under 3% of production for the Haynesville, Fayetteville, and Marcellus shale gas regions. Pétron et al. (2014) found leak rates of about 4% ± 1.5% of production for the Denver-Julesburg Basin, and Zavala-Araiza et al. (2015) found a leak rate of 1.5% (within a range of 1.2% to 1.9%) for the Barnett shale region. Based on studies at scales ranging from individual equipment to regions, Brandt et al. (2014) concluded that leakage rates are unlikely to be large enough to make the impact of natural gas to the climate as large as that of coal over a period of 100 years.

A fundamental question explored by recent studies is why some studies that use "top-down" methods to quantify basin-wide emissions, such as atmospheric observations made using light aircraft, suggest higher emissions than those estimated by official inventories, such as the U.S. Environmental Protection Agency's (U.S. EPA) Greenhouse Gas (GHG) Inventory (U.S. EPA

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2017a). Official inventories sometimes have been found to omit sources. For example, Marchese et al. (2015) found large emissions from sources in the gathering sector, which previously were not included in the U.S. GHG Inventory but have since been incorporated. However, the main source of the discrepancy may be the existence of a small number of "superemitters" (Brandt et al., 2014). For example, Zavala-Araiza et al. (2015) estimated that half of CH_4 emissions from the Barnett region were due to 2% of oil and gas facilities. They estimate that 30% of production sites emitted more than 1% of natural gas produced and that these sites accounted for 70% of emissions from production sites. The existence of superemitters raises the possibility that CH_4 emissions can be reduced with fewer, targeted actions, with adequate monitoring and maintenance of equipment.

Some studies focused on specific processes also have found lower emissions than inventories. Lamb et al. (2015) found that emissions from natural gas distribution were 36% to 70% lower than emissions from the 2011 U.S. EPA inventory that was based primarily on data from the 1990s. Marchese et al. (2015) found that emissions from processing plants were a factor of 1.7 lower than the U.S. EPA 2012 inventory and three times higher than U.S. EPA's GHG Reporting Program (U.S. EPA 2017a). On the other hand, the researchers found evidence that emissions from gathering facilities could be significantly higher than U.S. EPA estimates. Zimmerle et al. (2015) found that emissions related to transmission and storage could be lower than inventory estimates. U.S. EPA's GHG Inventory has since been updated to include data from these studies. Finally, as suggested by Schwietzke et al. (2017), top-down estimates also are subject to biases, such as sampling midday when episodic emissions from manual liquid unloadings are more likely. This study highlights the difficulty in extrapolating information that is limited in space and time, such as aircraft campaigns, to annual timescales as needed for comparison to inventories.

Based on measurements of ethane (C_2H_6) and CH_4 in the global atmosphere and firn air, Simpson et al. (2012) and Aydin et al. (2011) found that CH_4 emissions from global oil and natural gas production likely increased until the 1980s and since then have leveled off or decreased. Ethane is co-emitted by oil and natural gas production from thermogenic origin; however, it does not have microbial sources, making it a potentially useful indicator of some CH_4 oil and natural gas emissions. Schwietzke et al. (2016) used global observations of the methane isotopologue $^{13}CH_4$, which can be used to distinguish microbial and thermogenic emissions, to show that oil and natural gas CH_4 emissions have been stable over the past several decades, even as production has significantly increased, implying that fossil fuel production has become more efficient. They also found that global emissions of fossil fuel CH_4 are likely 50% to 100% higher than previous estimates, although their higher estimates include emissions from geological seeps, a source that has not been widely considered in the global CH_4 budget. Schwietzke et al. (2016) estimate that global emissions are likely to be in the range of 150 to 200 teragrams (Tg) CH_4 per year. Only a small fraction of global emissions from oil and gas production (less than 10 Tg CH_4 per year) are thought to be from the United States (U.S. EPA 2017a).

The implications of not accurately measuring and, if large, mitigating these emissions are very significant. As noted above, leakage rates of roughly 3% per year can "flip" CH_4 from a fuel cleaner than coal in immediate global warming impact to emissions larger than a conventional coal-fired power plant (see also Allen et al., 2013; Brandt et al., 2014; Howarth et al., 2011; Karion et al., 2013; Kort et al., 2008; Miller et al., 2013; Pétron et al., 2014; Schneising et al., 2014; and U.S. EPA 2013, 2014, 2015b).

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To assess the impacts of leakage on the roles of natural gas in an integrated portfolio that includes large amounts of renewable power, a series of scenarios was run within the SWITCH-WECC model to identify least-cost electric power grids capable of meeting emissions goals (Fripp 2012; Mileva et al., 2013; Nelson et al., 2012). SWITCH-WECC includes a detailed representation of existing generators, storage facilities, and transmission lines in the Western Electricity Coordinating Council (WECC), which roughly spans the western portion of North America but does not explicitly model natural gas wells, pipelines, or related infrastructure. SWITCH makes construction and dispatch decisions for renewable and traditional generators, along with transmission and storage to minimize the levelized cost of delivering electricity over its planning horizon. The WECC area provides a useful lens because the United States is the largest global consumer of natural gas and has recently set policy goals to reduce leakage as well as overall GHG emissions.

is extremely diverse in its sources and magnitudes; less than 1% of equipment can be responsible for most facility and pipeline leaks (Frankenberg et al., 2016; U.S. EPA 2006b; Zavala-Araiza et al., 2015). The overall GHG intensity of natural gas electricity is highly dependent on fugitive CH_4 emissions from leakage in the fuel supply chain. Methane, the principal component of natural gas, is a GHG that is between 28 and 86 times[12] more potent than CO_2 in 20- and 100-year time frames, respectively (Myhre et al., 2013; Stocker et al., 2013), leading to temporal accounting issues similar to those for bioenergy systems (Ocko et al., 2017).

3.4.6 Feedbacks

There are many different plausible feedback mechanisms (both positive and negative) that could affect the North American energy system's ability to continually provide sufficient, reliable, and affordable energy. Three types of energy system–related feedbacks include those associated with changes in climate, other exogenous forces, and internal dynamics. This section provides illustrative examples of each.

A changing climate is likely to affect energy demand and production, although the scale and direction of this effect are debated (Wilbanks et al., 2007). For example, increasing temperatures may reduce heating demand in high latitudes while increasing cooling demands in areas with warmer climates (Hadley et al., 2006; Zhou et al., 2013, 2014). Research in the last decade has analyzed this relationship at fine spatial and temporal scales, highlighting differences with larger-scale assessments. For example, the difference between today's annual total U.S. energy consumption and projected consumption from 2080 to 2099 is less than 2% under a changing climate, but changes per month at the scale of individual states are larger, with summer electricity demand increasing by more than 50% and nonelectric energy needs in springtime declining by 48% (Huang and Gurney 2016).

There also may be linkages between increased temperatures and thermoelectric capacity, as anticipated changes in the hydrological cycle likely will exert constraints on electricity generation. Warming is expected to lead to decreasing river discharge in some areas and increasing river temperatures (Huntington 2006; van Vliet et al., 2016). Elevated water temperatures, along with changes in urban water availability due to climate change and competing pressures on upstream water sources, are likely to make water cooling of thermoelectric power plants (both fossil and nuclear) less efficient. Furthermore, water shortages for urban residents (McDonald et al., 2011) may

[12] The global warming potential (GWP) of methane (CH_4) varies across time because of its relatively short half-life in the atmosphere. Because this half-life changes somewhat according to carbon-climate feedbacks, CH_4 GWP for the 100-year and 20-year time frames ranges from 28 to 34 and 84 to 86, respectively (see Myhre et al., 2013).

limit their ability to allocate water resources for other uses, including electricity generation.

An example of another potential exogenous feedback mechanism in the energy system is increased disease pressure on forests and increased forest vulnerability to fire, which could reduce wood availability for those depending on bioenergy (see Ch. 9: Forests, p. 365). While these pressures may contribute to long-term bioenergy loss, they could contribute to increases in bioenergy feedstocks in the short term. However, relatively little is known, for example, about how mortality due to pine bark beetles affect important aspects of forest regeneration and hence future bioenergy resources (BANR 2017).

Finally, feedbacks created by changes in the energy system itself may become important. For example, growing fleets of plug-in electric vehicles could increase electricity demand in the transportation sector, which today is fueled mostly with petroleum. U.S. DOE (EIA 2018f) projects that combined sales of new electric, plug-in hybrid electric, and hybrid vehicles will grow in market share from 4% in 2017 to 19% in 2050, translating into a vehicle fleet of over 2 million. This increase in electric vehicle charging will be a significant new source of electricity demand and will change the dynamics and extent of peak demand. These shifts can be met with smart meters, time-based rates, and electric grid management techniques, or through costly additions to power capacity (U.S. DOE 2015b). Alternatively, if the trend toward microgrids and distributed energy increases, there could be lower levels of electricity carried throughout the national grid, leaving room for other uses. Both the forward trends and the implications of these feedback mechanisms are uncertain, and the subsequent impacts on the carbon cycle contributions from the North American energy system remain unknown. An incomplete understanding of the feedback mechanisms, therefore, poses concern for future energy planning. Follow-up studies (*sensu* Wilbanks et al., 2007), which report on the effects of climate change on energy production and use, could focus on the variety of potential feedbacks, the costs of their impact on energy systems, and subsequent potential trends in carbon contributions to the atmosphere. Furthermore, studies could explore how the outcomes of these feedbacks might affect the vulnerability of the energy system.

3.5 Global, North American, and Regional Context

North America's annual share of global CO_2e emissions reached its first peak during the 1920s, when the share ranged from 50% to 58% of total emissions, which at that time were 490 to 550 Tg C (1.8 to 2.0 Pg CO_2e). By 1945, global emissions levels reached 672 Tg C (2.5 Pg CO_2e) per year, at which point North America accounted for about 59% of total annual emissions.[13]

Thereafter, North America's annual share started a monotonic decline that, by 2008 despite reaching an absolute regional high of 1,830 Tg C (6.6 Pg CO_2e), was less than 21% of the total annual global emissions. By 2013, the North American annual share of total global emissions was down to 17%. The cumulative share from North America has been steadily falling since the late 1950s, when it was about 43%, to 2013 when it stood at around 29% (see Figure 3.9, p. 141). The declining annual and cumulative shares of North American energy-related CO_2e emissions demonstrate the growing influence of fossil fuel combustion in emerging economies.

3.6 Societal Drivers and Impacts

This section focuses on the drivers of changes in the North American energy system and how these drivers have influenced changes in carbon cycle dynamics. A driver is any natural or human-induced factor that directly or indirectly causes a change in the system (see, for example, Nelson 2005). Drivers often are divided into categories, such as direct versus indirect, proximate versus primary, and immediate versus underlying. These distinctions attempt to identify the speed and scale at which the driver operates and the driver's linkage to the environmental state.

[13] For a discussion of how long these emissions might stay in the atmosphere, see Ch. 8: Observations of Atmospheric Carbon Dioxide and Methane, p. 337.

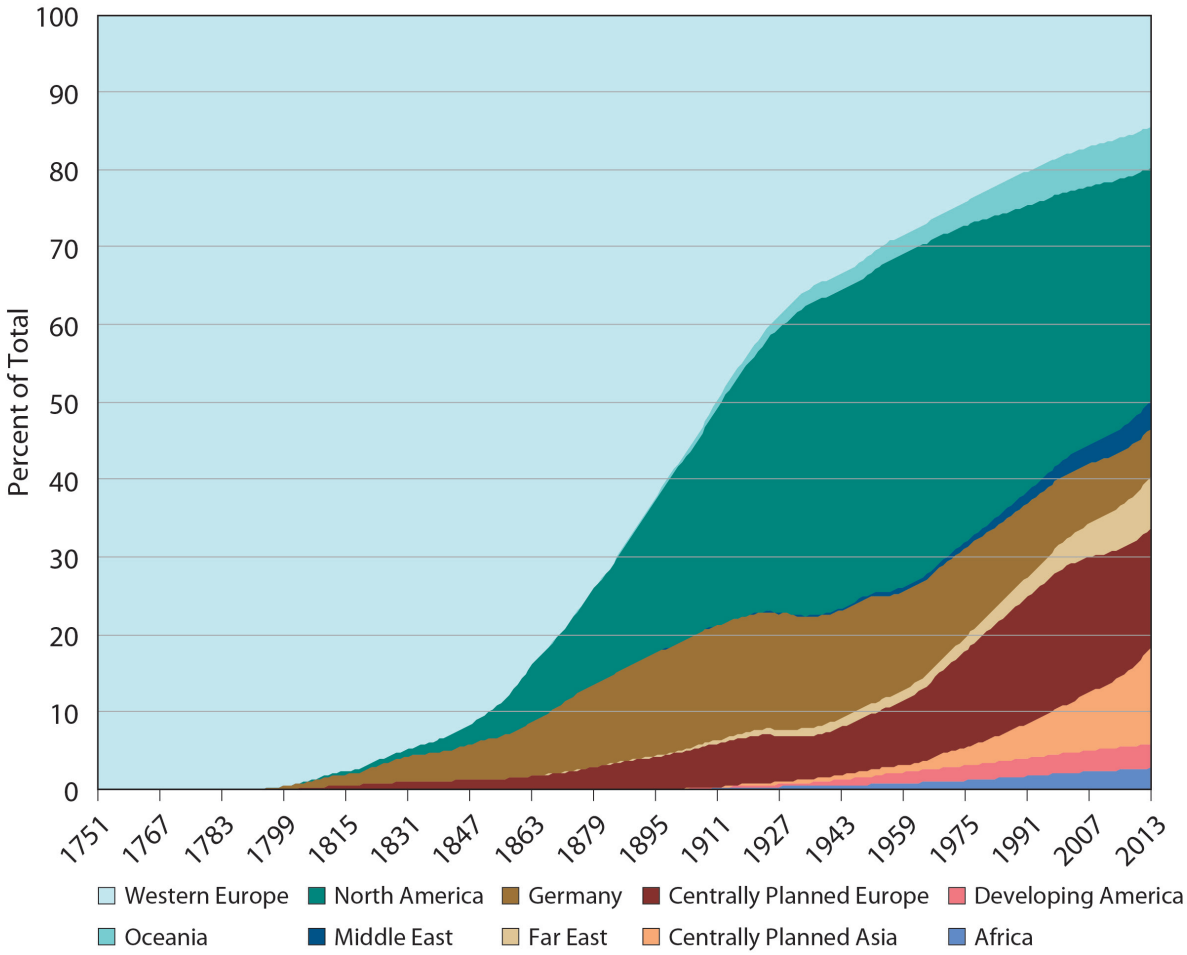


Figure 3.9. Change in Cumulative Share of Carbon Dioxide Emissions from Fossil Fuel Burning, Cement Manufacture, and Gas Flaring. Percentages are by region, from 1751 to 2013. [Data source: Boden et al., 2016.]

The first systematic discussion of drivers of environmental change emerged as the IPAT identity, where environmental impact (I) was estimated by multiplying the population (P) by affluence (A) and by technology (T; for a review, see Rosa and Dietz 2012). Subsequently, the drivers (PAT) were identified as primary or indirect, given that they work largely through other drivers. For example, with increasing affluence, households have more expendable income to consume energy (via air conditioning, for example) and subsequently increase their energy use (Sivak 2013; Davis and Gertler 2015). The point is that increasing affluence operates through both population units (households) and increases in energy consumption via more expendable income. The IPAT equation has expanded into a much more complex set of influences that help to explain environmental change (see, for example, Reid et al., 2005; Marcotullio et al., 2014).

The IPAT equation was the model for the Kaya Identity, named after Yoichi Kaya, which provides similar multiplicative elements to help explain the change in CO_2 emissions (Rosa and Dietz 2012; EIA 2011b).

$$F = P \times G/P \times E/G \times F/E$$

The formula for primary drivers of carbon emissions (F) includes population (P), GDP per capita

(G/P), energy per GDP output (energy intensity, E/G), and carbon emissions per energy input (carbon intensity, F/E). Often the formula also includes sectoral structural changes. The variables in the equation are factors that include a much larger number of proximate or direct influences such as fuel price, resource availability, infrastructure, behavior, policies and other processes, mechanisms, and characteristics that influence emissions (see, for example, Blanco et al., 2014; Table 3.3, p. 127). The Kaya Identity accounting categories often are used in the decomposition of emissions and provide an overarching framework for examining societal influences as well as a template for scenario development (Nakicenovic 2004). This section addresses the main factors identified in the Kaya equation. For a discussion of local influences on the carbon cycle, see Ch. 4: Understanding Urban Carbon Fluxes, p. 189; for social and behavioral influences on the carbon cycle, see Ch. 6: Social Science Perspectives on Carbon, p. 264; for policy influences from respective governmental policies at the international, national, and state or provincial levels, see Section 3.7, p. 149.

Figure 3.10, p. 143, presents the factors of the Kaya Identity, along with total energy use, in a simple decomposition analysis for the North American region. Several points become evident in this graph, including those between 2007 and 2015: 1) population and GDP per capita increased by approximately 8% and 18%, respectively; 2) energy intensity and carbon intensity decreased by about 25% and 6.4%, respectively; and 3) emissions and energy use decreased by around 11% and 4.5%, respectively. That is, since 2007, while regional population and GDP per capita increased, energy use and energy-related CO_2e emissions decreased. The following subsections examine the factors in more detail to explain what happened. Each subsection includes a description of the factor and how it theoretically affects energy and emissions levels, along with a review of what actually happened, at the regional scale and for each economy.

3.6.1 Population Growth

The current population of North America is almost half a billion people and growing. The most populous nation in the region, the United States, continues to grow and is projected to do so at an annual rate of 0.34% through the end of this century, when population is estimated to reach approximately 648 million (UN 2015). Although growing populations can increase energy use and subsequent carbon emissions, this is not universally true. Increases in population do not necessarily produce proportional changes in environmental stress. Thus, population may have an elastic (greater than 1) or inelastic (less than 1) effect on emissions. If the impact is elastic, greater population will produce more problems such as traffic congestion, resulting in greater emissions than expected based merely on the proportion of increased population. The larger the city, the greater the congestion, and therefore the impact may be disproportionate compared to the growth of the population. Alternatively, larger populations may induce economies of scale and enable more efficient use of resources, thereby lowering the impact on emissions levels. In this case, the impact of population growth would be inelastic.

Between 2005 and 2015, North America grew by an estimated 45 million people (approximately 1.0% annually), and yet energy use and CO_2e emissions have declined. Alternatively, Mexico's population has increased commensurately with national energy use and carbon emissions. During this period in Mexico, however, emissions first increased with population and then decreased even as population continued to increase.

3.6.2 Financial Crisis and Declines in GDP Growth

Increasing affluence can either increase emissions levels through increased consumption per capita or mediate emissions through shifts in the scale or composition of consumption. In 2008, the world experienced the global financial crisis, which hit particularly hard in North America. Feng et al. (2015, 2016) argue that the economic crisis, through

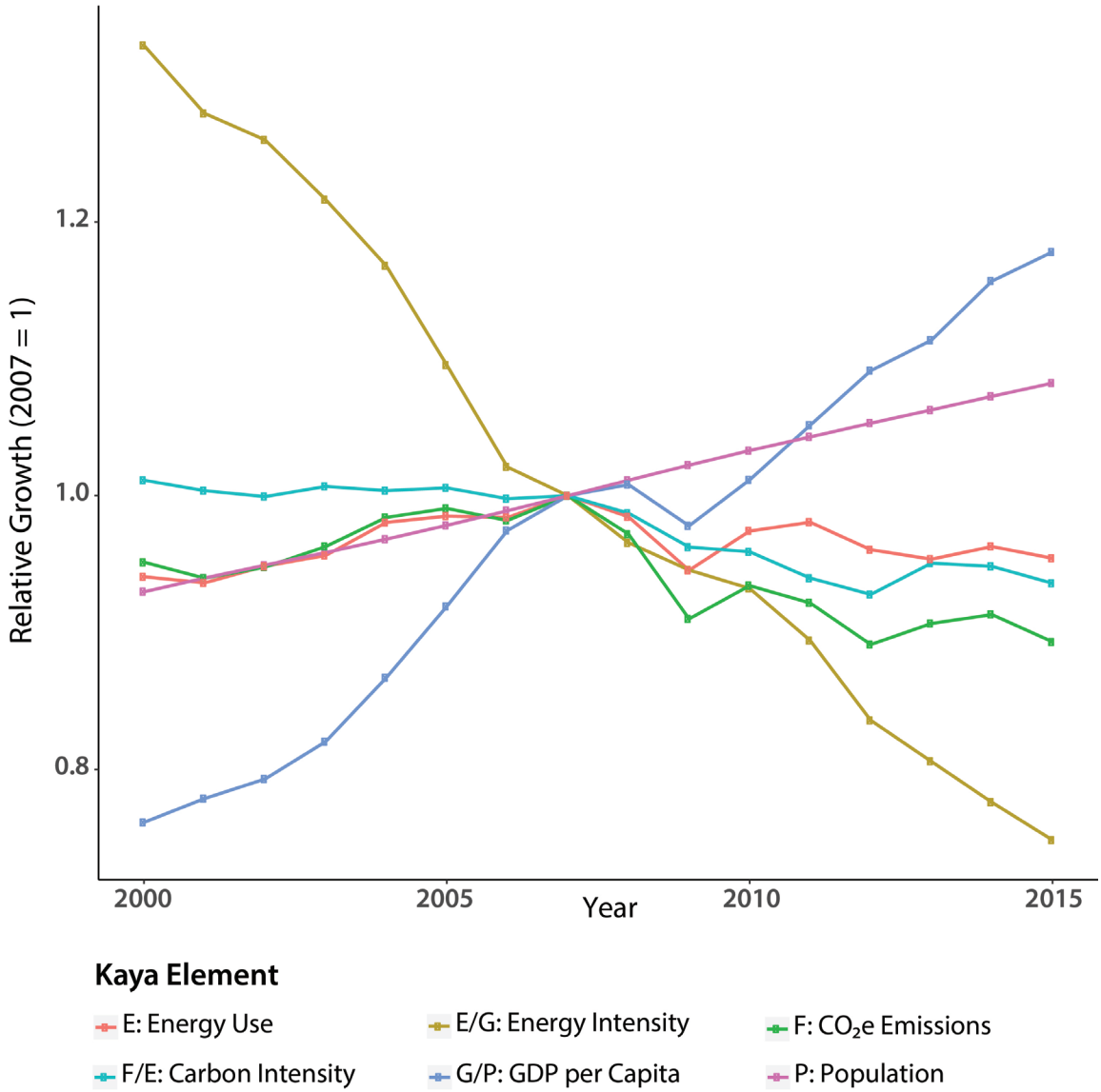


Figure 3.10. Kaya Identity Decomposition, 2000 to 2015. Key: CO_2e, carbon dioxide equivalent; GDP, gross domestic product. [Data sources: EIA 2017i and World Bank 2017.]

lowering GDP per capita, also decreased the volume of consumed goods and services and was responsible for 83% of the decrease in U.S. emissions from 2007 to 2009, which totaled around 0.6 Pg CO_2e (164 Tg C), or 9.9% of the nation's total. This decrease makes up the bulk of the regional change during that period.

However, according to the World Bank (2016c), the GDP for North America in 2007 was $17.7 trillion; after declining for several years, it rebounded by 2013 to reach $18.7 trillion (all values in this paragraph are in US$ 2010). By 2016, the region's GDP was $19.9 trillion, or over 20% higher than in 2007. The per capita GDP by country also followed the

same trajectory. In 2007, the approximate GDPs per capita were $48,600 for Canada, $9,300 for Mexico, and $50,000 for the United States. After falling to lows of $46,500, $8,700, and $47,600 respectively, in 2009, each country's GDP per capita figures had equaled or exceeded 2007 levels by 2012. By 2015, Canada's GDP per capita was $50,300, Mexico's was $9,600, and the United States' was $52,000 (World Bank 2018). Despite increases in GDP combined with population growth, energy use and CO_2e emissions have remained below 2007 levels. According to Shahiduzzaman and Layton (2017), from 2010 to 2014 real GDP per capita growth and population factors (without any mitigating effects) would have resulted in yearly CO_2 emissions increases of 25.5 Tg C annually (14.8 Tg C due to increases in GDP per capita and 10.8 Tg C due to population increases). Over the 5-year period from 2010 to 2014, therefore, an increase of approximately 127 Tg C was offset by other factors. Clearly, while the economic downturn was significant for the initial change in emissions trend, it does not account for the continued reduced energy use and GHG emissions from North America's energy systems.

3.6.3 Reduced Energy Intensity

Energy intensity is the amount of energy per GDP output (E/G). When economic growth outpaces the increase in primary energy supply, energy intensities decrease. Therefore, lowering energy intensities can represent mitigation gains, if benefits of efficiencies are not offset by greater use. Over the long term, energy intensities in Canada and the United States have been declining, due partly to increases in the efficiency of fuel and electricity use, including a shift from large synchronous generators to lighter-weight gas-fired turbines and new fuel sources (e.g., renewables; U.S. DOE 2015b; see Section 3.4.3, p. 131), and partly to changes in economic structure and saturation of some key energy end uses.

In the United States, from 1950 to 2011, energy intensity decreased by 58% per real dollar of GDP and is projected to drop 2% annually to 2040 (EIA 2015c). U.S. energy intensity in 2011 was approximately 7.73 megajoules (MJ) per US$1 purchasing power parity (PPP). Since 2004, the United States experienced a 1.6% drop annually in its energy intensity. Canada has some of the highest energy intensities of the IEA countries (IEA 2010). Canada's energy intensity remains the highest among the regional economies and in 2011 was approximately 11.2 MJ per US$1 PPP. Canada's geography, climate, and industrial structure, including its export-oriented fossil fuel industry, make it a highly energy-intensive country. Like the United States, however, its energy intensities also experienced significant decreases over the last half of the past century (EIA 2016c). Over the past decade, Canadian energy intensity dropped 1.5% annually, and since 1971 it has dropped by 39%. Decreases have been attributed largely to increased contributions of low energy–using commercial activities relative to high energy–using manufacturing, as well as the rapid growth of the Canadian economy compared to population growth (Torrie et al., 2016). These economic structural changes are more important to the nation's falling energy intensity than increasing energy efficiencies. Recently, Mexican energy intensity also has been falling, but only slightly. Mexico, an emerging economy, had been increasing its energy intensity, but over the past decade it fell by 0.04% annually. Mexico's energy intensity is now about 5.5 MJ per US$1 PPP.

An examination of the efficiency gains across sectors of the North American energy system demonstrates structural changes in end-use energy sector components. For example, reduced energy intensity in the electricity-generation sector can be tracked by heat rates. Average operating heat rates for coal and oil power plants for 2015 in the United States are 32.5% and 31.9% efficient, respectively, for power plant type. Average U.S. operating heat rates for gas-fired plants are around 43% efficient (EIA 2016a). However, gas turbine and steam generators typically have the lowest efficiencies, while combined-cycle plants have the highest. For example, in 2016, gas turbines were 25.2% and 30.4% efficient for oil and gas energy sources, respectively, while combined-cycle plants reached efficiencies of 34.6% and 44.6% for oil and gas, respectively (EIA 2018d). The

Table 3.4. LEED-Certified Buildings and Gross m² Coverage in North America (2016)[a,b]

Area	Certified		Registered		Grand Total	
	Number	m² (millions)	Number	m² (millions)	Number	m² (millions)
Canada	399	3.97	218	5.01	617	8.98
Mexico	172	2.46	496	11.83	668	14.29
United States	24,777	299.28	31,212	447.26	55,989	746.54
North America	25,348	305.71	31,926	464.10	57,274	769.81

Notes

a) Source: United States Green Building Council 2016, www.usgbc.org/advocacy/country-market-brief.

b) LEED, Leadership in Energy and Environmental Design.

increased share of natural gas–fired plants and the greater use of high-efficiency combined-cycle plants have helped to reduce the overall energy intensity of the U.S. electricity-generation system (Nadel et al., 2015). Notwithstanding the importance of economic structural changes in Canada's decline in energy intensity, business energy intensity experienced a decline from 1995 to 2010 (22% of total decline), and increases in efficiencies in power generation contributed to this decline but only slightly (5% of total decline; Torrie et al., 2016). Mexico is undergoing a major set of policy reforms to open up its power sector, including the electricity system. Actions focused on reducing generation costs include reducing heat rates and losses from transmission and distribution, all of which will improve the electricity system's energy efficiency (CEE and ITAM 2013; Robles 2016).

Energy-efficiency improvements in appliances and utilities, residential and commercial buildings, industrial, and transportation sectors also have slowed growth in North American energy demand and helped to decouple energy demand growth from GDP. The U.S. national efficiency standards implemented since 1987 have saved consumers 9.22 GJ or 21% of household electricity usage in 2015 (deLaski and Mauer 2017). Further, these efficiencies are expected to save 74.9 EJ of energy (cumulative from 2015) by 2020 and nearly 149.8 EJ through 2030 (U.S. DOE 2017b). The cumulative utility bill savings to consumers are estimated to be more than $1 trillion by 2020 and more than $2 trillion by 2030 (U.S. DOE 2017b). Utility energy-efficiency programs for the residential sector are achieving incremental savings of about 30.6 PJ annually, equivalent to 0.7% of all electricity sales with a cumulative impact many times this value, most at a cost of US$0.030 per kWh (Hoffman et al., 2017). While these savings are impressive, energy consumption for appliances and electronics continues to rise and the increasing number of devices has offset gains in appliance efficiency (EIA 2013a).

Independently, building codes reduced residential electricity consumption in the United States by 2% to 5% in 2006 (CEC 2014). Energy savings through building codes have been supplemented by the increase in green buildings. For example, from 2003 to 2016 the number of Leadership in Energy and Environmental Design (LEED)–certified buildings in the United States increased from 116 to over 24,700, those in Canada increased from 3 to 399, and the number in Mexico increased from 0 to 172 (see Table 3.4, this page). The United States Green Building Council estimates that green building, on average, currently reduces energy use by 30%, carbon emissions by 35%, and water use by 30% to 50%, also generating waste cost savings of 50% to 90%. A rapidly increasing market uptake of currently available and emerging advanced energy-saving technologies

could result in annual reductions of 1.7 Pg CO_2e (464 Tg C) emitted to the atmosphere by 2030 in North America, compared to emissions under a "business-as-usual" approach (Commission for Environmental Cooperation 2008). In Canada from 1990 to 2013, residential- and commercial-sector energy efficiencies improved by 45% and 33%, respectively. Canadian space heating energy intensity alone was reduced by over 38% as households and commercial and institutional offices shifted from medium- to high-efficiency furnaces, improved thermal envelopes for buildings (e.g., insulation and windows), and increased efficiencies of various energy-consuming items such as auxiliary equipment and lighting (Natural Resources Canada 2016b). In Mexico, energy efficiency in the residential and commercial sector has focused on lighting, appliance, and equipment replacement (IEA 2015b). In the United States, the share of space heating and cooling for residential energy consumption has been falling due in part to the adoption of more efficient equipment and better insulated windows. An increasing number of residential homes are built to ENERGY STAR® specifications (U.S. EPA 2015c), lowering their energy consumption to 15% less than that for other homes. U.S. households are increasingly incorporating energy-efficient features; in 2011, ENERGY STAR® homes made up 26% of all new homes constructed (EIA 2011c, 2012a).

Industries also have experienced lower energy intensities through shifts in technologies and greater efficiencies. For example, energy use in U.S. steel production has been declining. From 1991 to 2008, there has been a 38% decline in the total energy consumption used in the industry. The largest portion, 34% of the decline in the total energy consumption, occurred between 1998 and 2006 (EIA 2017f). In Mexico, the efficiencies of thermal power generation and of the power sector as a whole have been increasing rapidly since 2002 (from 38% to 45% in 2010 in the case of thermal power generation). This recent improvement is due to a switch in the power-generation mix to natural gas and to the spread of gas combined-cycle plants. In 2010, the gas combined-cycle power capacity accounted for 43% of the total thermal capacity. The country's chemical industry also has experienced drops in energy intensity, falling by nearly 7% per year between 1994 and 2009 (ABB 2012). In Canada, industrial oil production has been driven primarily by a rapid rise in the extraction of bitumen and synthetic crude oil from the nation's oil sands operations, where total output has increased by 140% since 2005. This has contributed to the 37-Tg increase in CO_2e (10.1 Tg C) emissions from mining and upstream oil and gas production from 2005 to 2015. However, from 2010 to 2015 the emissions intensity of oil sands operations themselves have dropped by approximately 16% as a result of technological and efficiency improvements, less venting emissions, and reductions in the percentage of crude bitumen being upgraded to synthetic crude oil (ECCC 2017b).

In the North American transportation sector, there have been considerable improvements in efficiency over the past decade as well as reductions in fuel use in vehicle miles traveled. The on-road transportation sector, in particular, has seen reductions in fuel use for both total and per capita vehicle kilometers traveled, as well as reductions in emissions of CO_2e. According to the U.S. Department of Transportation (U.S. DOT; U.S. DOT 2016), from 2005 to 2015 total average kilometers traveled per passenger vehicle dropped from approximately 20,100 to 18,200 and total average fuel use per passenger vehicle dropped from around 2,100 liters (L) to 1,800 L. As a result, total average kilometers per liter (km/L) of fuel consumed increased from 9.4 to 10.1. These efficiencies have been driven by changes in vehicle weight and power and by corporate average fuel economy (CAFE) standards. For example, according to U.S. DOT (2014), CAFE fuel standards have increased from 11.7 km/L in 2010 to 14.5 km/L in 2014 (based on projected required average fuel economy standard values and model year [MY] reports). In 2015, while total U.S. vehicle travel distance was 4% higher than that in 2007, CO_2e emissions for transportation were 1.73 Pg CO_2e (472 Tg C), or about 8% lower compared with 1.89 Pg CO_2e (515 Tg C) in 2007 (U.S. EPA 2016).

Motor gasoline consumption has not exceeded the previous 2007 peak (EIA 2016i). From 1990 to 2013, Canada also experienced energy-efficiency improvements in the transportation sector by 27%, while energy use in the sector increased during this period by 20% (Natural Resources Canada 2016b). From 2004 to 2013, Canadian transportation energy use and emissions stayed fairly level at approximately 0.17 Pg CO_2e (46.4 Tg C; ECCC 2016b). Similar to the United States, the majority of transportation emissions in Canada are related to road transportation. The growth in road transportation emissions for the country is due largely to more driving. Despite a reduction in kilometers driven per vehicle, the total vehicle fleet has increased by 19% since 2005, most notably for both light- and heavy-duty trucks, leading to more kilometers driven overall (ECCC 2017b). According to IEA (2017a), from 2007 to 2013, Mexico's transportation CO_2e emissions increased by 2.2% annually, amounting to 10% of the total increases during this period. Emissions for this sector are expected to increase further to 2040 as demand for personal vehicles increases in Mexico (SEMARNAT-INECC 2016).

Similar trends in the United States and Canada can be seen in freight rail transport, with decreases in U.S. freight rail fuel consumption and small increases in Canada (Statistics Canada 2016; U.S. DOE 2014a). Substantial increases in fuel consumption in the international aviation sector have occurred over the past decade for both U.S. and Canadian flights (Natural Resources Canada 2016d; U.S. DOE 2014b).

Overall, in both Canada and the United States, a large portion of fuel and electricity use, associated with residential energy use and personal transportation, is weakly coupled with positive change in GDP. Research in Canada suggests that personal transportation and household energy, which compose about a third of the nation's total energy use, are not coupled to GDP growth, resulting in an overall decrease in energy intensity when GDP rises, even if there is no economic structural change or efficiency improvement (Torrie et al., 2018). This result has been a major contributor to declining energy intensities in Canada and possibly also in the United States during recent decades.

In summary, energy-intensity decreases have been an important factor in the current trends of CO_2e emissions for North America. Shahiduzzaman and Layton (2017) calculated that, between 2005 and 2010 and between 2010 and 2014, decreases in energy intensity of output were responsible for annual reductions of 19.2 Tg C and 21.7 Tg C from the U.S. energy system, respectively. Over the 10 years of these two periods, this trend translates to about 409 Tg C, which is offset by decreases in energy intensity.

3.6.4 Decreasing Carbon Intensity

The carbon intensity (F/E in the Kaya Identity) of energy use is another factor, like energy intensity, that affects the overall level of emissions from the energy system. Different fossil fuels have different carbon intensities (e.g., per unit of energy, coal emits about 50% more CO_2 than that by refined petroleum products), and some energy forms, like solar, wind, and nuclear, do not emit CO_2 at all. The mix of fuels being used in a society changes over time and with it the carbon intensity of the energy system. Changes in the carbon intensity of the North American energy system over the past decade have been significant and mostly evident in the United States and Canada, although Mexico also has contributed to the decreasing trend.

In the United States, carbon intensities for all major energy sectors have been dropping steeply since 2005. The greatest declines were experienced by the industrial and electricity sectors. The industrial sector produced the least amount of CO_2 per unit of primary energy consumed in 2016, with emissions of 41.5 kg CO_2e per GJ. The electric power sector, which is second only to the transportation sector, produced 45.3 kg CO_2e per GJ in 2016, which is now below the commercial and residential sector's carbon intensities (EIA 2017j). Shahiduzzaman and Layton (2017) calculate that U.S. carbon intensity

reductions have offset approximately 287 Tg C from the U.S. energy system over the past 10 years.

Canada's carbon intensities have also been decreasing. Similar to the United States, decreasing energy generation from coal and oil and increasing generation from hydropower, nuclear, and wind were the largest drivers of the 31% decrease in emissions associated with electricity production between 2005 and 2015. The permanent closure of all coal-generating stations in the province of Ontario by 2014 was an important factor in changing the national fuel mix (ECCC 2017b).

After falling during the 1990s, Mexico's carbon intensity increased between 2000 and 2010 (OECD 2013). Mexico's CO_2e emissions profile is heavily skewed toward transportation and the power sector. The ongoing effort to switch from oil- to gas-fired generation has reduced the carbon intensity of Mexico's electricity sector by 23% since 2000, and further improvements are expected (IEA 2016b).

Changes in the carbon intensity in North America are related to several trends, some of which have already been discussed in detail.

- The natural gas boom, including the shift from coal to cheaper and cleaner natural gas for electricity production and industrial processes (EIA 2017j), with the critically important caveat that venting, flaring, and fugitive emissions may be underestimated (see Section 3.4.2, p. 129, and Box 3.3, p. 137).
- Increased renewables in the fuel mix in all North American countries, including wind, solar, and bioenergy (with caveats mentioned for this last source; see Sections 3.4.3, p. 131, and 3.4.5, p. 135), driven, in part, by declining costs and changing fuel prices.
- A wide range of new technologies including grid-scale electricity storage and alternative fuel vehicles.

Many new technologies affect the potential of others. For example, improvements in electric vehicle battery technology help support improvements in utility energy storage. Energy storage improves grid stabilization and buffers peak electricity demands that, in turn, help support a larger share of renewables in the electric grid.

Other important technologies include the grid-scale electricity storage (i.e., previously mentioned new battery storage for wind and solar) and alternative fuel vehicles. Grid-scale electricity storage currently includes pumped hydroelectric storage but, in the future, also may be enhanced by a wide variety of technologies that serve an array of functions within the electric power system (EIA 2011a). There are currently 40 pumped storage plants in the United States totaling more than 22 GW of capacity (about 2% of the nation's generating capacity; EIA 2013b). Canada has one pumped storage facility in Ontario with a 174-MW capacity, and Mexico is currently exploring the possibility of developing this technology.

With the transportation sector having the highest carbon intensity in the region, use of alternative fuel vehicles can help make significant reductions. These vehicles are designed to operate on fuels other than gasoline and diesel, including compressed natural gas, propane, electricity, hydrogen, denatured ethanol, and other alcohols and methanol. An example of the increase can be seen in the electric vehicle stock. Globally, electric vehicles surpassed 1 million in 2016. In the United States, there have been recent increases in the number of electric vehicles on the road from around 23,000 in 2011 to 118,000 in 2015, and Canada's electric vehicles jumped from fewer than 1,000 to almost 7,000 during this same period (EV-Volumes 2017). Mexico currently is focusing on increasing biofuels for its vehicle fleet. With the 2017 launch of the Tesla Model 3, the number of electric vehicles may increase (Marshall 2017).

Notwithstanding the emergence of these new technologies, an important influence that has underpinned the current decrease in carbon intensity is falling energy prices. Among different fossil fuel

choices, falling prices for one fuel relative to another provide incentives to consumers to shift fuels. According to Houser et al. (2017), the surge in U.S. natural gas production due to the shale revolution made coal increasingly uncompetitive in U.S. electricity markets. Coal also faced growing competition from renewable energy.

Oil, gas, and coal prices have all dropped recently. From 2014 to 2015, world oil prices dropped dramatically and, to a lesser extent, so did natural gas and coal prices. From 2010 to mid-2014, global crude oil prices were relatively stable but historically high, at more than US$100 per barrel. In June 2014, Brent crude oil, a key global crude oil pricing benchmark, traded above US$110 per barrel. Later in 2014, oil prices began to drop, and, by January 2015, prices had declined by about 60% to under US$46 per barrel. Both Brent and West Texas Intermediate, a benchmark for U.S. crude oil, remained in the range of US$40 to US$60 per barrel for much of 2015 (National Energy Board 2016). The collapse in prices was driven by a marked slowdown in demand growth and record increases in supply, particularly tight oil (sometimes called shale oil) from North America, as well as a decision by the Organization of Petroleum Exporting Countries (OPEC) not to try to rebalance the market through cuts in output (IEA 2015a).

Differing from oil, there is no global pricing benchmark for natural gas. Instead, the three major regional markets (North America, Asia-Pacific, and Europe) have different pricing mechanisms. In North America, gas prices are determined at hubs and reflect local gas supply and demand dynamics. Notwithstanding the different market conditions, the surge in natural gas production within North America has reduced prices. While natural gas prices declined globally, the pace and extent were dramatic in North America. In the United States, for example, the average price for natural gas to power plants dropped from $10 per thousand cubic feet (ft^3) in 2008 to $3 in 2016, a 71% decline (US$ 2016). During this period, despite falling coal prices, the average delivered cost of coal to power plants decreased by only 8% in real terms (Houser et al., 2017; IEA 2015a).

The increase in low-carbon energy sources also has been driven in part by falling costs of renewables. Globally, bioenergy-for-power, hydropower, geothermal, and onshore wind projects commissioned in 2017 largely fell within the range of generation costs for fossil-based electricity. Drivers of cost reductions include technological improvements, competitive procurement, and a large and growing base of experienced project developers (IRENA 2018a). In North America, between 2008 and 2016, the price of onshore wind declined by 36%, and the price of solar PV modules fell by 85% (Houser et al., 2017), prompting expansion in these PV sources. Wind prices are projected to be competitive with natural gas by 2050 (U.S. DOE 2017a). The cost of distributed generation, specifically distributed rooftop PV systems, also is declining. Median installed prices for distributed PV systems declined 6% to 12% per year from 1998 to 2015, and the decline was faster after 2009 (Barbose and Dargouth 2016).

Declining costs of renewable power generation along with increased competition from cheap natural gas are responsible for 67% of the decline in U.S. domestic coal consumption (Houser et al., 2017). Although low prices in natural gas relative to those of oil and coal have helped to reduce carbon intensities, continued low fossil fuel prices also can decrease pressure to develop renewables, possibly pushing carbon intensities in the opposite direction. IEA (2017a) suggests that this dynamic will affect conditions in the near future, unless the price of fossil fuels increases.

3.7 Carbon Management Decisions

Historically, governmental management and policy have been capable of changing the North American energy system in significant ways including, for example, the creation of the Tennessee Valley Authority in the United States; construction of the U.S. national highway system and the Grand Coulee and Hoover dams; development of the National and Pacific railroads in Canada; and Mexico's national

highways development and, until recently, governmental control of Mexico's oil, gas, and electric energy system. Governmental carbon management decisions can be identified through plans and commitments, investments in infrastructure and research and development, market-based tools, and regulations and standards at multiple levels of government. Indeed, over the past decades, there have been significant international, national, subnational or state, and city actions and commitments that have shaped the current regional carbon management system. Over the past year in the United States, however, national energy policy has been changing (EY 2017). This section reviews selected international, national, and state or subnational governmental actions in North America and their effects on energy use and carbon emissions trends.

3.7.1 International Carbon Management Decisions and National Responses

Parties to the Paris Agreement[14] are required to submit mitigation contributions that describe national targets, policies, and plans for reducing carbon emissions. The targets in these contributions are "nationally determined" and not legally binding. Over 190 countries have submitted nationally determined contributions under the Paris Agreement including GHG emissions reduction targets and related actions (UNFCCC 2015; IEA 2015a; World Resources Institute 2016a). In North America, Canada has announced a GHG emissions reduction target of 30% below 2005 levels by 2030. Mexico has announced a GHG emissions reduction target of CO_2e and short-lived climate pollutant reductions of 25% by 2030 with respect to a business-as-usual scenario, as well as additional reductions possible in the context of international financial support. Prior to the adoption of the Paris Agreement, the United States put forward a nonbinding Intended Nationally Determined Contribution (INDC) of reducing emissions 26% to 28% below 2005 levels by 2025. On June 1, 2017, President Trump announced that the United States intends to withdraw from the Paris Agreement, unless it identifies better terms for participation, and that the United States would cease implementation of this nationally determined contribution (Executive Office of the President 2017).

In 1994, Canada, Mexico, and the United States established the North American Agreement on Environmental Cooperation (NAAEC) to ensure that economic activities among the countries would not come at the expense of the environment. NAAEC provided for the establishment of the Commission for Environmental Cooperation (CEC), the first collaborative trilateral venue promoting a cooperative approach to environmental protection in the region. The strategic priorities for 2015 to 2020 include climate change mitigation and adaptation. The initiatives under this priority include developing, comparing, and implementing actions to mitigate CO_2e emissions, consistent with international commitments and piloting protocols in key sectors (e.g., waste management, the food industry, and transportation) to reduce emissions of short-lived climate pollutants, such as black carbon and CH_4 (Commission for Environmental Cooperation 2015).

In 2012, national climate action plans described commitments and strategies for reducing carbon emissions and are coordinated through policies to meet countries' announced GHG reduction targets and actions. Mexico in 2012 became the first emerging economy to pass comprehensive climate change legislation, and in 2015 it became the first emerging economy to release its post-2020 climate action plan. Mexico is undergoing a process that further details what the announced emissions target and actions mean at the sectoral level. The country's Energy Transition Law (*Ley de Transición Energética*) of 2015, as part of its energy reform program (*Reforma Energética*) that started in 2013, includes clean (i.e., low- or no-emission) energy targets of 25% of electricity generation by 2018, 30% by 2021, and 35% by 2024. The way in which this law is implemented will affect Mexico's emissions pathway. Canada's action plan includes working with provinces and territories to establish

[14] The Paris Agreement (UNFCCC 2015) resulted from the United Nations Framework Convention on Climate Change (UNFCCC) 21st Conference of the Parties (COP21).

a pan-Canadian framework for addressing climate change, including carbon pricing; investments in clean energy technology, infrastructure, and innovation; and a Low-Carbon Economy Trust Fund to support provinces and territories in achieving emissions reductions and transforming their economies toward a low-carbon future (ECCC 2016a). In the United States, a number of climate action policies have been put in place to encourage energy efficiency and renewable energy generation. Recently, the United States announced an energy policy, defined in the *America First Energy Plan*, aimed to promote domestic energy generation, including oil, coal, and natural gas extraction and use, as part of a broader strategy of energy security and independence. Because this strategy is still under development, it cannot be evaluated in this report.

3.7.2 National Energy and Carbon Management Decisions

Investments to increase energy efficiency and lower carbon emissions were promoted in recent economic recovery acts in Canada and the United States. In the United States, the American Recovery and Reinvestment Act (ARRA) of 2009 provided US$17 billion for energy efficiency and US$26 billion for renewable energy investment. Federal support for clean energy technology across agencies totaled an estimated US$44 billion and grew to US$150 billion from 2009 to 2014 (Banks et al., 2011). These actions played a role in reducing the levelized cost of energy (LCOE) for onshore wind technologies and lowering the capital costs of wind and solar PV technologies. ARRA also funded US$4.5 billion for smart grid demonstration projects, US$700 million for alternative fuel vehicles, and US$400 million for U.S. DOE's Advanced Research Projects Agency-Energy (ARPA-E) and allowed energy-efficiency improvements to be eligible for billions of dollars in investment for federal agencies. Within the United States, discussions of improving infrastructure have focused on roads, bridges, airports, and other public works, possibly including energy infrastructure. As highlighted earlier, rebuilding the country's aging energy infrastructure also would increase energy efficiencies.

Similarly, Canada's recovery plan included a 2-year stimulus package worth CAD$35 billion. Approximately CAD$12 billion was earmarked for infrastructure, launching one of the largest building projects in the country's history (Whittington and Campion-Smith 2009). More than CAD$300 million was designated for the ecoENERGY Retrofit program, which provides financial support to homeowners, small- and medium-sized businesses, public institutions, and industrial facilities to help them implement energy-saving projects that reduce energy-related GHGs and air pollution. Approximately CAD$1 billion was apportioned for clean energy research, development, and demonstration (RD&D) projects (Department of Finance Canada 2009). As with the United States, infrastructure improvements are likely to alter future energy-use trajectories.

Although Mexico did not implement a recovery act, in December 2013 it passed an energy reform bill as part of the *Reforma Energética,* which opened the country's energy sector for significant regulatory, financing, and infrastructure changes for both renewable and nonrenewable sources to meet the reform bill's promised increase in production. The Mexican *National Infrastructure Program 2014–2018*, in adherence to the *National Development Plan 2013–2018*, promotes development of energy generation, transmission, and distribution facilities that will make use of potential renewable energy and has invested an estimated US$46 million in 138 strategic electricity infrastructure projects (PricewaterhouseCoopers Mexico 2014). Additionally, recent partnerships with private companies and finance have spurred infrastructure expansion (Zborowski 2015).

A number of market-based tools are also available to governments. At the national scale, Mexico passed a carbon tax in 2014 on fossil fuel sales and imports (natural gas and jet fuel were exempted) as part of broader fiscal reform. The tax is set at approximately US$3.50 per megagram CO_2e. Firms are allowed

to use credits from a domestic clean development mechanism offset program to fulfill their tax liability, but the operating rules for this mechanism have yet to be published (ICAP 2016). Canada recently announced the implementation of a national carbon tax. Prime Minister Justin Trudeau said a minimum price of US$10 per ton of CO_2e would be implemented in 2018, rising to US$50 per ton by 2022.

The United States imposes few energy-related "green taxes" at the federal level. An exception includes the "gas guzzler" tax on new automobiles that exceed fuel efficiency standards (Cohen et al., 2015). Rather, the United States uses tax credits, subsidies, and support services to incentivize targeted investments. These include the investment tax credit (ITC), which is a key driver for solar energy. The credit provides a 30% tax credit for solar energy systems for residential and commercial buildings. The tax credit has played a role in the increase of solar investments, which have grown by more than 1,600% from 2006 to 2014 (SEIA 2014). The production tax credit (PTC) also supports the development of renewable energy, most commonly wind, though it also applies to geothermal and some bioenergy systems. The PTC provides an incentive of 2.3 cents per kWh, for projects under construction in 2015, for the first 10 years of a renewable energy facility's operation and is adjusted over time, reducing the value of the incentive to 40% of the PTC for projects that start construction in 2019 (Union of Concerned Scientists 2014).

Subsidies are an important way that governments continue to promote their energy policy. In 2009, according to IEA et al. (2010), global fossil fuel subsidies were estimated at US$312 billion and rose to US$409 billion in 2010 (up almost 30% from 2009), six times the amount allotted for renewable energy support (IEA et al., 2011). Eliminating these subsidies globally would cut energy-related CO_2 emissions by an estimated 13% (Ball 2013). In the United States, subsidies for fossil fuels from 2002 to 2008 reached US$72 billion, with an additional set of subsidies for renewable fuels totaling US$29 billion (Environmental Law Institute 2009). Canada also subsidizes fossil fuel industries for around CAD$3.3 billion for oil and gas producers (Touchette 2015). One result of the restructuring of Mexico's state-run energy program is that fossil fuel subsidies have dropped from US$19.1 billion in 2012 to US$5 billion in 2014 (IEA 2015c).

Governmental agencies may provide support services with goals to enhance investment, research and development, and collaboration with private-sector firms. U.S. DOE's Office of Energy Efficiency and Renewable Energy (EERE), for example, was created to promote and sustain leadership in the transition to an economy powered by clean, affordable, and secure energy. This program's goal is to accelerate the development and adoption of fuel-efficient and nonfossil fuel transportation technologies, renewable sources of electricity, energy efficiency in residential and commercial buildings, reductions in life cycle energy consumption of manufacturing processes, and new grid technologies (U.S. DOE 2015c). EERE's SunShot program was developed with the goal of reducing solar costs to US$1 per watt for utility-scale solar systems (and US$1.50 per watt for residential) by 2020. However, in 2017 U.S. DOE announced that the solar industry had already achieved the SunShot Initiative 2020 solar cost targets, bringing the costs of utility-scale solar to $0.06 per kWh. Models of the impact of this price change on the U.S. energy sector suggest solar power can cost effectively provide up to about one-third of national electricity capacity by midcentury (Mileva et al., 2013). The rapid deployment of distributed generational solar power systems over the past 5 to 10 years has both highlighted challenges and demonstrated many successful examples of integrating higher penetration levels than previously thought possible (Palmintier et al., 2016). Not only is future expansion of solar possible, but this expansion potentially could provide a significant number of jobs in energy sectors of the country and the world (Wei et al., 2010; IRENA 2018b).

Regulatory approaches also can have an impact on the energy sector. The U.S. Clean Air Act (CAA), for example, was established in 1963 but

strengthened in 1970 in conjunction with the creation of U.S. EPA to carry out programs to regulate air pollution nationwide. CAA authorizes EPA to set national standards for clean air, and, as of 2009, the legal foundation was established for U.S. EPA to regulate GHGs under CAA. CAA benefits have been massive, estimated to reach approximately (US$ 2006) $2 trillion in 2020 with costs of only (US$ 2006) $65 billion (U.S. EPA 2011). In 2012, Canada passed regulations to establish a regime for reducing CO_2 emissions resulting from electricity production that uses coal as a fuel; these regulations took effect in 2015.

Governments commonly use regulatory standards to enforce policy goals. Since 1987, for example, national standards for appliance efficiency have been developed and subsequently expanded to more than 50 categories of products used in homes, businesses, and industry (de Laski and Mauer 2017). Another important example in the United States consists of CAFE standards (dating back to the 1970s), which were designed to improve vehicle fuel economy. U.S. EPA and U.S. DOT's National Highway Traffic Safety Administration (NHTSA) issued final rules extending the national program to further reduce GHG emissions and improve fuel economy for MYs 2017 through 2025 light-duty vehicles. U.S. EPA established national GHG emissions standards under CAA, and NHTSA established CAFE standards under the Energy Policy and Conservation Act, as amended by the Energy Independence and Security Act. The new standards are estimated to lead to corresponding reductions in CO_2 emissions totaling 491 Tg C during the lives of light-duty vehicles sold in MYs 2017 to 2025 (U.S. EPA and U.S. DOT 2012). As of March 2017, however, EPA reopened a midterm review of U.S. CAFE standards that would require the industry to deliver a fleet average of at least 23 km/L (54.5 miles per gallon) by 2025. The type of changes introduced to these regulations during the review and their impacts are not yet clear.

Canada established the Company Average Fuel Consumption (CAFC) targets and harmonized them with CAFE standards in the United States. The main difference between Canada's CAFC regulations and the U.S. CAFE program was that Canada's standards remained voluntary for 25 years. The Motor Vehicle Fuel Consumption Standards Act of 1982 set legally binding standards parallel to U.S. CAFE regulations, but lawmakers did not officially implement the program until 2007. In 2010, new regulations were the first in Canada to limit GHG emissions from the automotive sector under the Canadian Environmental Protection Act of 1999. The final Passenger Automobile and Light Truck Greenhouse Gas Emission Regulations set fuel economy targets for passenger vehicles and light-duty trucks similar to those of the United States (Feldman 2009). In 2013, the Mexican government published final standards regulating CO_2e emissions and the fuel economy equivalent for new passenger vehicles, including cars, pickup trucks, and sport utility vehicles. The final standard will apply to vehicle MYs 2014 to 2016. Taking into account all annual credits (except credit banking and trading), the standard is expected to result in a new car fleet average fuel economy of 14.6 km/L in 2016 (ICCT 2013). These laws put all three countries on track for a target of 20.9 km/L of gasoline equivalent by 2025 (ICCT 2013).

3.7.3 Subnational Energy and Carbon Management Decisions

While U.S. federal actions discussed in the previous section have prompted changes in national carbon management and may change the direction of future trends, important carbon management decisions also happen at the subnational level in states and localities (see Ch. 4: Understanding Urban Carbon Fluxes, p. 189, for elaboration on the urban carbon management initiatives). For example, in Canada, the provinces have been active in setting carbon taxes, fuel economy standards, and emissions controls prior to the national government's actions (IEA 2010). In the United States, state governments have implemented policies on energy and GHG emissions including GHG targets, caps, and pricing; renewables; CCS; nuclear power; transportation; energy efficiency; methane and hydrofluorocarbons; and forestry and land use (America's Pledge 2017). Some states have developed and implemented several

multistate carbon cap-and-trade partnerships. One of the most notable multistate programs is the Regional Greenhouse Gas Initiative, which began as a collaboration between 10 northeastern states to cut their CO_2 emissions. At the state and provincial level, renewable portfolio standards (RPS) have been implemented as a mechanism to encourage the uptake of renewable energy in the United States as part of federal policy, but the details of implementation are left to the states to choose. As of 2013, 29 states plus Washington, DC, have some form of enforceable RPS, and eight other states have nonbinding renewable portfolio goals (EIA 2012d). Energy-efficiency resource standards also have been popular in subnational units. In 1999, Texas became the first state to establish an energy-efficiency resource standard. As of 2015, 25 states have adopted such a standard. The American Council for an Energy Efficient Economy found that most states are on target to meet their goals (Sciortino et al., 2011). Many tribes are also prioritizing energy-efficiency and renewable-energy projects (Norton-Smith et al., 2016). More than 275 American cities, counties, tribes, and states have created green building codes, which have promoted energy efficiency in this sector. Leading states include California, Virginia, and Washington.

Other subnational carbon management programs include energy-efficiency standards; public benefit funds; electric grid standards; feed-in tariffs;[15] on-bill financing;[16] property-assessed clean energy; and the use of subsidies, tax credits, and rebates to promote clean energy. In Mexico, the Federal District of Mexico City has implemented Bus Rapid Transit routes and created emissions standards for vehicles (see Ch. 4: Understanding Urban Carbon Fluxes, p. 189). U.S. states and Canadian provinces also have been active in promoting transportation policies, including procurement of hybrid or electric vehicles for their fleets, creating strict emissions standards for cars and light trucks, promoting low-emissions vehicle standards and zero-emissions vehicle promotions and production requirements. For example, California's "Advanced Clean Cars Program" allows the state to set and enforce vehicle emissions standards more stringent than standards set by U.S. EPA. Whether and how this law will be affected by the revision to U.S. federal CAFE regulations is not yet clear. Finally, many states have set emissions-reduction plans to reach a goal of 30% or more reduction of CO_2e emissions by 2030 (Cohen et al., 2015). For example, New York state has implemented a plan to reduce GHG emissions by 40% from 1990 levels by 2030 and 80% by 2050 (NYSERDA 2015). In 2006, California passed the Global Warming Solutions Act and, subsequently, the Climate Change Scoping Plan as the roadmap to achieve reductions of 30% from business-as-usual emissions projected for 2020. The law spells out a range of measures to expand energy-efficiency programs; achieve a renewable energy mix; and develop a cap-and-trade program that covers 85% of the state's emissions, such as electricity generation, large industrial sources, transportation fuels, and residential and commercial uses of natural gas. In 2014, California linked its program to Canada's program in Quebec (Cohen et al., 2015).

In summary, a variety of policies at multiple levels of government have helped shape the patterns of energy use and carbon emissions in the region over the past decade. Recently, however, the U.S. federal government appears to be prioritizing energy resource extraction and use; how these policies will affect future trends remains uncertain.

3.8 Future Outlook

The future outlook for the North American energy system is based on scenario analyses. Scholars have argued that scenarios are a good tool to analyze future trends while addressing uncertainties (Peterson et al., 2003; Schoemaker 1991; van Vliet and Kok 2015; van't Klooster and van Asselt 2011). Several different approaches to scenario

[15] Feed-in tariffs (FIT) are policy mechanisms used to encourage deployment of renewable electricity technologies. FITs typically guarantee that customers who own a FIT-eligible renewable electricity-generation facility, such as a rooftop solar photovoltaic system, will receive a set price for their utility for all the electricity they generate and provide to the grid.

[16] On-bill financing refers to loans made to utility customers, the proceeds of which would pay for investments in energy efficiency improvements. Regular monthly loan payments are then collected by the utility on the utility bill until the loan is repaid.

development exist, however (Amer et al., 2013; Börjeson et al., 2006; van Notten et al., 2003). While there are no consensus universal typologies, the review literature often includes three distinct types of scenarios: predictive, exploratory, and backcasting scenarios. This section describes these different scenario types, discusses the advantages and disadvantages of each approach, and reviews scenario results applied or related to the North American energy system and GHG futures. The scenarios reviewed provide information on energy and GHG predictions based on historical and current policies, the future range of plausible outcomes defined by variations in energy and emissions drivers, and the costs of mitigating carbon emissions to create average global temperature increases of not more than 2°C.

3.8.1 Energy and Carbon Emissions Forecasts

Predictive scenarios comprise two different types—forecasts that address how the future will unfold, based on likely development patterns and "what if" scenarios that respond to changes in specified events or conditions (Börjeson et al., 2006). Forecasts typically provide a reference case result that may be accompanied by outcomes of high- and low-type scenarios, indicating a span of options. Sometimes probabilities are employed in attempts to estimate likelihoods of outcomes. Predictive scenarios are useful to stakeholders for addressing foreseeable challenges and opportunities and can increase the awareness of problems that are likely to arise if specific conditions are fulfilled. This type of scenario attempts to answer the question, what *will* happen? (Quist 2013).

An important criticism of predictive scenarios is that they have a self-fulfilling nature resulting from assumptions of continuity based on past and current trends. Predictive scenarios are based on historical data that define the trends and model parameters that do not change over the course of the scenario timescale (i.e., no policy changes are identified initially), preventing the possibility of transformational changes.

The forecasts examined here include national future projections of CO_2e for Canada (ECCC 2016c), the United States (EIA 2017k), and Mexico (IEA 2016b). Each projection set includes a reference case and a defined set of high- and low-emissions scenarios. In all cases, the figures are modeled as projections of "what if" forecasts, given certain assumptions about drivers. The methods and assumptions among the projections presented are neither standardized nor bias-corrected. Despite uncertainties in combining figures, these aggregate national projections are useful in signaling the variety of potential futures for North American energy system emissions.

In its *Annual Energy Outlook*, EIA (2017k) provides a "Reference" case projection as a business-as-usual trend estimate, given known technology and technological and demographic trends. It generally assumes that current laws and regulations affecting the energy sector, including sunset dates for laws that have them, are unchanged throughout the projection period. The potential impacts of proposed legislation, regulations, and standards are not reflected in this reference case. The cases of "High emissions" and "Low emissions" are based on different assumptions of macroeconomic growth, world oil prices, technological progress, and energy policies. "High emissions" cases include scenarios with high economic growth and those without the U.S. Clean Power Plan (CPP). "Low emissions" cases include scenarios with low economic growth and those with CPP. All projections are based on results from EIA's National Energy Modeling System (NEMS). The EIA (2017c) "Reference" case assumes that current laws and regulations remain in effect through 2040 and that CPP is implemented. The "Reference" without CPP case is the "High emissions" scenario and has similar basic assumptions to the "Reference" case, but it assumes high economic growth and no implementation of a federal carbon-reduction program. The "Low emissions" case is the low economic growth scenario and assumes GDP annual growth at 1.6% (compared with a 2.2% reference case).

The U.S. "High emissions" scenario projects an increase in emissions of 0.7% (10.4 Tg C) from 2015 to 2040, while the "Low emissions" scenario projects a decrease in emissions of 12.2% (175.3 Tg C) during this period. Across the three presented alternative cases, total energy-related CO_2e emissions in 2040 vary by more than 185.5 Tg C (14% of the "Reference" case emissions in 2040). The "Reference" case projects a decrease of emissions by 7.2% from 2015 to 2040, translating into a decrease of 103.9 Tg C. The U.S "Low emissions" case translates into an emissions reduction about equal to the current size of Canada's total energy-related emissions. Note, however, that even with the low-growth emissions case, the U.S. energy system would not meet the target of reducing emissions by 26% to 28% below 2005 levels (1,640 Tg C) by 2025 (a drop of 426 Tg C and 469 Tg C, respectively), previously proposed in the U.S. INDC (The Record 2016).[17] Although the United States has stated an intent to withdraw from the Paris Agreement, this comparison illustrates the kind of reductions needed to meet the goals of the United Nations Framework Convention on Climate Change (UNFCCC) 21st Conference of the Parties (COP21). Note that even if all signatories of the Paris Agreement met their reduction goals, it is unclear whether global temperature increases would be kept below an average temperature increase of 1.5°C above preindustrial levels (Clémonçon 2016; Rogelj et al., 2016, 2018; Obersteiner et al., 2018).

Canada's energy-related CO_2e emissions projections are published by ECCC (2016c) and derived from a series of plausible assumptions regarding, among others, population and economic growth, prices, energy demand and supply, and the evolution of energy-efficiency technologies. The projections also assume no further governmental actions to address GHG emissions beyond those already in place as of September 2015. In the Canadian projections, the "Reference" scenario represents the midrange levels for economic growth (1.5% to 2.2% GDP growth rates per year), stable population growth (1.1% to 1.3%), and slight increases in energy prices, among other factors. The "High emissions" scenario includes high GDP annual growth rates (1.3% to 2.7%) and high energy prices, among other factors. The "Low emissions" scenario includes assumptions of low GDP annual growth (0.8% to 1.5%) annually and low energy prices. Environment and Climate Change Canada uses the Energy, Emissions and Economy Model for Canada (E3MC; ECCC 2016c). Canadian emissions from stationary combustion and fugitive sources, transportation, and industrial processes are presented; emissions from agriculture and waste are excluded. Also, the Canadian projections are for the years up to 2030. The 2030 figures are used here for the 2040 North American analysis.

In the Canadian "Reference" case, Canada's energy-related emissions by 2030 are 180 Tg C, an increase of 3.6% from 2015 levels. The "High emissions" scenario projects 193 Tg C levels by 2030 (an increase of 10.8% from 2015 levels). The "Low emissions" case projects 168 Tg C by 2030 (a decrease of 3.6% from 2015 levels). The range in emissions represents 14% of the reference case emissions in 2030. Also note that for Canada, in the "Low emissions" scenario, the nation's energy system would meet its Nationally Determined Contribution (NDC) target of 142.64 Tg C by 2030 (ECCC 2017a).

IEA (2016b) recently provided projections for Mexico under a variety of scenarios. The IEA analysis includes five different scenarios: "New Policies," "Current Policies," "450 Scenario," "No Reform," and "Enhanced Growth." The "New Policies" scenario

[17] In preparation for the Conference of the Parties for the United Nations Framework Convention on Climate Change (UNFCCC), negotiating parties were invited to submit Intended Nationally Determined Contributions (INDCs). INDCs publicly outlined what post-2020 climate actions (including targets for emissions levels) were intended by each signatory under the new international agreement. The actions were "intended" prior to the Paris Agreement, but when a country became a signatory, the plans became Nationally Determined Contributions (NDCs). The United States submitted an INDC and became a signatory to the agreement, but it has subsequently announced its intention to withdraw from the agreement, a process which cannot happen until after 2020 (https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&clang=_en). Both the governments of Canada and Mexico have ratified the Paris agreement.

reflects the way governments envision their energy sectors developing over the coming decades. Its starting point is the policies and measures that are already in place, but it also takes into account, in full or in part, the aims, targets, and intentions that have been announced. "Current Policies" depicts national energy system growth without implementation of any new policies or measures beyond those already supported by specific implementing measures in place as of mid-2016. No allowance is made for additional implementing measures or changes in policy beyond this point, except when current measures are specifically time-bound to expire. The "450 Scenario" is the decarbonization strategy, which has the objective of limiting the average global temperature increase in 2100 to 2°C above preindustrial levels. The "No Reform" case is an illustrative counterfactual case that deliberately seeks to portray what might have happened to Mexico in the absence of its energy reform initiative announced in 2013. Finally, "Enhanced Growth" uses a higher assumption of GDP. This chapter identifies the reference case as the "New Policies" scenario, "Current Policies" is the high-emissions case, and the low-emissions case is the "450 Scenario."

Among these scenarios, changes in Mexican CO_2 emissions from 2014 to 2040 range by 50%. The reference case ("New Policies") projects an increase in emissions from 118 to 124 Tg C (5.6% increase) during the period. The high-emissions case ("Current Policies") projects an increase in emissions from 118 to 140 Tg C (19% increase). Alternatively, the low-emissions case ("450 Scenario") projects a decrease of almost 34%, with levels in 2040 reaching 78 Tg C. With the 450 Scenario, Mexico still will not meet its NDC target of reducing unconditionally 25% of its GHG emissions (below the business-as-usual scenario) for the year 2030. That is, the required 25% of the business-as-usual case (i.e., reference scenario) is a reduction of 29.3 Tg C (or 25% of 117 Tg C), but the reduction by 2030 using the 450 Scenario is 20 Tg C (117 to 97 Tg C). Again, these projections demonstrate the difficulty of meeting targets set forth by the Paris Agreement.

In aggregate, the data from these various models project future North American energy-sector emissions ranging from 3.0% higher than 2015 levels to 12.8% lower than 2015 levels by 2040 (see Figure 3.11, p. 158, and Table 3.5, p. 159). The aggregate "Reference" cases project a total 5.3% decrease in emissions from around 2015 by 2040. To ascertain a sense of uncertainty of these figures, the range of emissions from this set of projections is compared with regional estimates from private-sector forecasts of BP (2016) and ExxonMobil (2017), along with those of IEA (2016a). Both BP (2017a) and ExxonMobil (2017) project decreases in North American emissions. ExxonMobil (2017) projections, which include only the United States and Canada, suggest a 14.5% decrease in emissions by 2040 compared with 2015 levels, while BP (2017a) projections, which include all three nations, suggest an 11.8% decrease from 2015 to 2035. IEA (2016a) projections, which include the United States and Canada, show emissions levels rising by 10.5% between 2014 and 2030. This comparison identifies a wider range of future energy-related carbon emissions for North America than the national projections, suggesting a large range of predicted futures. Even at the aggregate "Low emissions" projection scenario, however, the region will not be able to meet the INDC and NDC commitments by 2040 (see Shahiduzzaman and Layton 2017).

3.8.2 Exploratory Energy and Carbon Emissions Scenarios

Exploratory scenarios sketch plausible futures, showing the implications of change in external drivers (Börjeson et al., 2006). Though not necessarily for prediction, they focus on what *may* happen, ultimately exploring uncertainty in driving forces (Börjeson et al., 2006; Shearer 2005; van der Heijden 2000). Typically, a set of scenarios are constructed to span a wide scope of plausible developments over a very long time span (Jefferson 2015).

The goals of exploratory scenario development include awareness raising of potential challenges, given a wide range of policies and outcomes, and deep insight into societal process interactions and influences (Peterson et al., 2003). In an exploratory

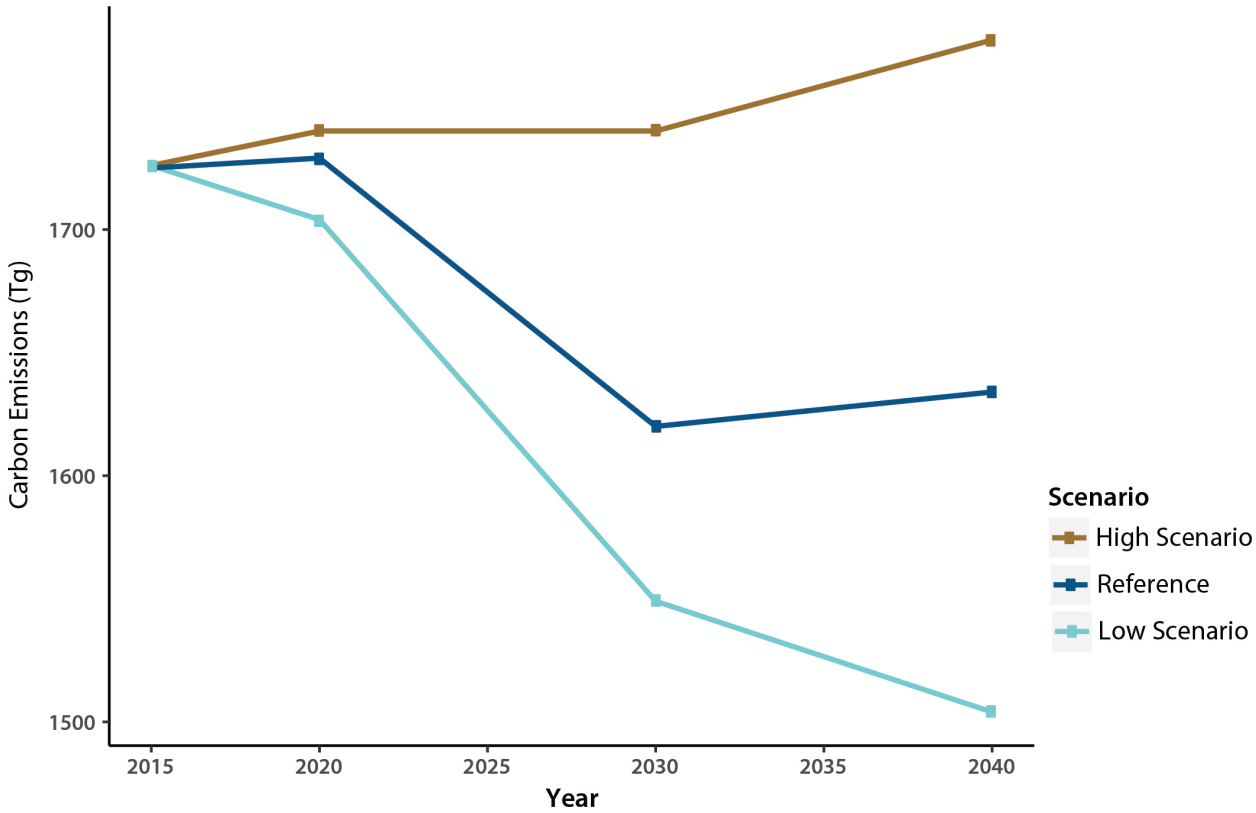


Figure 3.11. North American Energy System Carbon Emissions Scenarios in Teragrams (Tg). [Data sources: EEEC 2016c; EIA 2017k; and IEA 2016b.]

scenario exercise, the process of creating the scenarios is often as important as the product (van Notten et al., 2003). Exploratory scenarios address the question of what *can* happen in the future (Quist 2013). Besides providing a range of outcomes, from both well-understood and not so well-understood changes in conditions, exploratory scenarios have been found useful in accounting for important, but low-probability, condition changes. A criticism of exploratory scenarios is that, while they can demonstrate what might be possible, they are less useful in demonstrating how to achieve a desirable outcome (Robinson 1990).

Well-known examples of exploratory energy scenarios are those initially developed by Royal Dutch Shell and by the World Energy Council. The latest round of Royal Dutch Shell scenarios, titled *New Lens Scenarios: A Shift in Perspective for a World in Transition* (Royal Dutch Shell 2013), propose multiple lenses through which to view the future. The two pathways in the scenarios are called "Mountains" and "Oceans." These pathways are defined by different approaches to three key contemporary paradoxes (i.e., prosperity, connectivity, and leadership) and by how societies navigate the tensions inherent in each of these paradoxes. The "Mountains" pathway includes a world locked in *status quo*, tightly held in place by the currently influential powers. The rigid structure defined by the pathway is created by the demand for energy stability, which results in the steady unlocking of resources, but which also dampens economic dynamism and stifles social mobility. In the "Mountains" pathway, with the global energy supply remaining largely dominated by oil, natural gas, and coal, the world

Table 3.5. Projected Greenhouse Gas Emissions for North America (2015 to 2040)[a]

Economy	2015 (Tg C)[b]	2040 Reference Scenario (Range, Tg C)[b]	2015 to 2040 Percent Change in Reference Scenario (Range, Tg C)[b]
Canada (2015 to 2030)	173	180 (168 to 193)	3.6 (–3.6 to +10.8)
Mexico (2014 to 2040)	118	124 (78 to 140)	5.6 (–33.9 to +19.0)
United States (2015 to 2040)	1,434	1,330 (1,259 to 1,445)	–7.2 (–12.2 to +0.7)
North America	1,725	1,634 (1,504 to 1,777)	–5.3 (–12.8 to +3.0)

Notes

a) Sources: EIA 2017k; ECCC 2016c; IEA 2016b.

b) Tg C, teragrams of carbon.

overshoots the 2°C trajectory. During the second half of the century there remain opportunities for CCS technologies and zero-CO_2 electricity, but only if mandates promote policies for managing net global emissions.

The "Oceans" pathway, on the other hand, defines a world where power is devolved among competing interests and compromise is necessary. Economic productivity surges with waves of reforms, but social cohesion is sometimes eroded, resulting in political destabilization. In this pathway, market forces have greater prominence over governmental policies. In "Oceans," biomass and hydrogen play linchpin roles in energy systems by 2100, as oil, natural gas, and coal account for less than 25% of the world's energy supply, while solar, wind, and biofuels account for about 55%. Because of higher energy use, however, cumulative CO_2 emissions are 25% higher in "Oceans" than in "Mountains," and also, as in the "Mountains" pathway, global CO_2 emissions exceed the 2°C threshold. Thus, one of this study's key findings is that accelerated proactive and integrated policy implementation is necessary to avoid overshooting 2°C of globally averaged warming.

The World Energy Council (2016b) produced world energy scenarios to explore what the council called the "grand transition," which was emerging from underlying drivers that are reshaping energy economics. The outline of this transition is based on three exploratory scenarios projected to 2050: "Modern Jazz," "Unfinished Symphony," and "Hard Rock." The "Modern Jazz" scenario represents a digitally disrupted, innovative and market-driven world. "Unfinished Symphony" defines a future where intelligent and sustainable economic growth models emerge as the world moves to a low-carbon future. The "Hard Rock" scenario imagines a world of weaker and unsustainable economic growth with inward-looking national policies. Similar to the work of Royal Dutch Shell, mentioned previously, a key finding from the council's work is that limiting global warming to an increase of no more than 2°C will require an exceptional and enduring policy effort, far beyond already-pledged commitments and with very high carbon prices.

There also have been recent exploratory scenarios developed specifically for economies in North America. The Pew Center on Global Climate Change (Pew; Mintzer et al., 2003) and an Energy Modeling Forum (EMF) study (Clarke et al., 2014; Fawcett et al., 2014a), for example, explore plausible futures for the U.S. energy system. The Pew study describes three divergent paths for U.S. energy supply and use from 2000 to 2035. The creators argue that taken together, these scenarios identify key technologies, important energy policy decisions, and strategic investment choices that could enhance energy

security, environmental protection, and economic development over a range of possible futures. The first Pew scenario, called "Awash in oil and gas," describes a future of abundant supplies of oil and natural gas that are available to consumers at low prices. In this scenario, energy consumption rises and conventional technologies dominate the energy sector. This low–energy price pathway provides few incentives to improve energy efficiency and little concern for energy use. Carbon emissions rise 50% above the 2000 level by 2035. Pew calls the second scenario "Technology triumphs," which describes a future with a large, diverse set of drivers, converging to accelerate successful commercialization in the U.S. market of many technologies that improve energy efficiency and produce lower carbon emissions. U.S. companies play a key role in the subsequent development of an international market for these technologies. Sustained economic growth and increases in energy consumption are accompanied by a 15% rise in carbon emissions from 2000 levels by 2035. Finally, in Pew's "Turbulent world" scenario, U.S. energy markets are repeatedly battered by unsettling effects on energy prices and threats to U.S. energy security. High energy prices and uncertainty about energy supplies slow economic growth as the country moves from one technological solution to another, all of which have serious flaws, until finally settling on a program to accelerate the commercialization of hydrogen and fuel cells. Despite slower economic growth than in the other scenarios, carbon emissions still rise 20% above the 2000 level by 2035.

Climate change policy was deliberately excluded from the three Pew base case scenarios. To explore how these policies might affect outcomes, the project provided a climate policy overlay (described as a freeze on CO_2 emissions in 2010) and subsequent 2% per year decreases from 2010 to 2025, followed by 3% per year decreases from 2026 to 2035 for each scenario set to achieve the targeted emissions-reduction trajectory of at least 70% from 2000 levels by the end of the century. The portfolio of policies included 1) performance-based energy and emissions standards; 2) incentives to accelerate research and development into low-carbon technologies; 3) a downstream carbon emissions allowance cap-and-trade program applied to electricity generation, the industrial sector, and investment; 4) PTCs for efficiency improvements in energy and emissions technologies; and 5) "barrier busting" programs designed to reduce market imperfections and promote economically efficient decision making (for more details, see Mintzer et al., 2003). When the postulated policy overlay is applied to each base case scenario, it modifies the pattern of energy technology development and future emissions levels. In the "Awash in oil and gas" scenario, the policy overlay results in the highest costs to the economy to meet the carbon constraints with much more stringent policies than in the other scenarios. In the "Technology triumphs" scenario, the policy overlays reinforce the driving forces of the case and accelerate the commercialization of key technologies. In this case, climate policy is uncontroversial, and the United States becomes an international competitor in the development of next-generation energy supply and end-use technologies. In the "Turbulent world" scenario, the imposition of a carbon emissions constraint leads to significant reductions in oil demand and CO_2 emissions, decreases based on the emergence of new technologies that sweep the market in transportation and electricity production. All these cases demonstrate the possibility of meeting the goal of a 2°C carbon-reduction trajectory.

EMF is a structured forum for discussing issues in energy and the environment established in 1976 at Stanford University. EMF works through a series of working groups that focus on particular market or policy decisions. The EMF Model Intercomparison Project (MIP) number 24 (EMF24) was designed to compare economy-wide, market-based, and sectoral regulatory approaches of potential U.S. climate policy (Fawcett et al., 2014a).

The EMF24 project focused on policy-relevant analytics that engaged "what if" scenario analysis on the role of technology and scope of regulatory approaches. The effort used nine models to assess the implications of technological improvements

Table 3.6. Technological Assumptions in the Energy Modeling Forum Study[a]

Technology	Optimistic Technology	Pessimistic Technology
End-use energy	End-use assumptions that lead to a 20% decrease in final energy consumption in 2050 relative to the pessimistic technology, no-policy case.	Evolutionary progress. Precise assumptions specified by individual modeling teams.
Carbon capture and storage (CCS)	CCS is available. Cost and performance assumptions specified by individual modeling teams.	No implementation of CCS.
Nuclear	Nuclear is fully available. Cost and performance specified by each modeling team.	Nuclear is phased out after 2010. No new construction of plants beyond those under construction or planned. Total plant lifetime limited to 60 years.
Wind and solar energy	Plausibly optimistic technology development. Cost and performance assumptions specified by individual modeling teams.	Evolutionary technology development. Cost and performance assumptions specified by individual modeling teams.
Bioenergy	Plausibly optimistic level of sustainable supply. Supply assumptions specified by individual modeling teams.	Evolutionary technology development representing the lower end of sustainable supply. Supply assumptions specified by individual modeling teams.

Notes

a) Source: Clarke et al., 2014.

and technological availability for three scenarios: no emissions reductions (reference scenario), reducing U.S. GHG emissions 50% by 2050, and reducing U.S. GHGs 80% by 2050. The general technological assumptions include 1) an optimistic CCS or nuclear set of technology assumptions, which have pessimistic assumptions about renewable energy, and 2) an optimistic renewable energy set of technology assumptions for bioenergy, wind, and solar that do not allow CCS and phase out nuclear power energy (see Table 3.6, this page). The EMF24 scenarios allowed banking so that while cumulative emissions were consistent with an emissions cap that followed a linear path to 50% or 80% reductions (relative to 2005 levels) in 2050, actual modeled emissions could be higher. Reference scenarios did not include policies and served as counterfactual starting points for policy application. The policy assumptions explore these seven types of scenarios: 1) "Baseline with no policy," 2) "Cap-and-trade of varying stringency (0% to 80%)," 3) "Combined electricity and transportation regulatory," 4) "Electricity and transportation-sector policy combined with a cap-and-trade policy," 5) "Isolated transportation sector policy," 6) "Isolated electricity sector policy with a renewable portfolio standard (RPS)," and 7) "Isolated electricity sector policy with a clean energy standard (CES)."

The study finds that even under the most optimistic technology assumptions, no reference scenario among the different models meets the mitigation goals of 50% by 2050. The greatest average annual emissions reduction identified across models was 0.19% per year through 2050. Alternatively, every model could meet 50% reduction scenarios even under the most pessimistic assumptions about

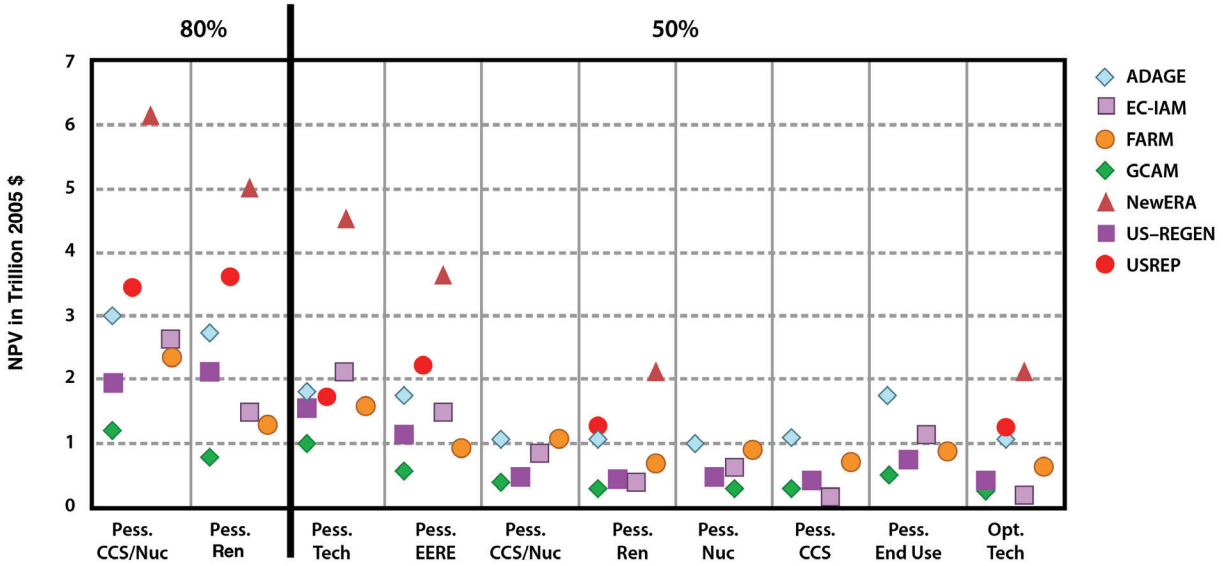


Figure 3.12. Net Present Value of Mitigation Costs from 2010 to 2050 from Seven Different Models. The measures presented are the total mitigation costs for 50% and 80% reductions in carbon emissions. Results suggest that total mitigation costs across pessimistic and optimistic technology assumptions (see Table 3.6, p. 161) are $1 trillion to $2 trillion (US$ 2005) for 50% reductions in GHG emissions and $1 trillion to $4 trillion (US$ 2005) for 80% reductions in GHG emissions. Among the caveats to these analyses, each of the models has different capabilities to calculate underlying metrics, so an assessment of costs generally must include different metrics across models, and these results do not include economy-wide impacts from the assumptions. Key: NPV, net present value; Pess., pessimistic; CCS, carbon capture and storage; Nuc, nuclear, Ren, renewables; Tech, technology; EERE, end-use energy and renewable energy; Opt., optimistic. [Figure source: Redrawn from Clarke et al., 2014, used with permission of *The Energy Journal*, conveyed through Copyright Clearance Center Inc.]

technology and produce the 80% reduction scenarios without nuclear and CCS, relying exclusively on renewable energy and end-use measures under different policy assumptions (Clarke et al., 2014). As in all other studies mentioned thus far, the EMF24 project confirms that mitigation at the 50% or 80% level will require a dramatic transformation of the energy system over the next 40 years.

Estimates from the EMF24 study indicate that the total mitigation costs of achieving 80% emissions reductions fall between $1 trillion and $4 trillion (US$ 2005) for most of the 80% emissions reduction scenarios through 2050, although one outlying model found costs as high as $6 trillion (US$ 2005) (Clarke et al., 2014; see Figure 3.12, this page). In the EMF24 study, not all models were able to report the same cost metrics due to structural differences, so the costs reported for each model reflect different ways of handling, such as the value of leisure time and costs associated with reduced service demands. A thorough description of the differences among these metrics can be found in Fawcett et al. (2014a).

Taken together, the Pew and EMF24 U.S. scenario analyses reveal three important conclusions: 1) the cumulative costs of mitigation for achieving an 80% emissions reduction (relative to 2005 levels) by 2050 fall between $1 trillion and $4 trillion (US$ 2005); 2) investment decisions today, especially those that support key technologies, will have a significant impact on North American energy-related carbon emissions tomorrow; and 3) a portfolio of policies

combining technology performance targets, market incentives, and price-oriented measures can help the United States meet complementary energy security and climate protection goals.

In summary, the differing exploratory scenarios provide a wide range of futures. All emphasize the importance of policy and technology development in guiding the world (see also IEA 2017c) and North America into a future of stable economic growth, global energy security, and reduced emissions. The finding that significant future emissions reductions require policy is further supported by the work of Shahiduzzaman and Layton (2017), who suggest that for the United States to achieve the 2025 target emissions levels, which are in line with the 2°C future world, the combined average annual mitigating contribution from energy efficiency, carbon intensity, and energy improvements will need to be at least 33% higher and as much as 42% higher than current trends portend, depending on the level of structure change in the U.S. economy.

3.8.3 Energy and Carbon Emissions Backcasting Scenarios

The third type of scenario includes normative, transformation studies. Typically, these scenarios start with the end state and work backwards, hence the name "backcasting" (Lovins 1977; Robinson 1982). Backcasting can be implemented in a large variety of ways (Quist 2007; Quist et al., 2011), although methods typically involve two steps: 1) development of desirable images of the future (visions) and 2) backwards analysis of how these visions can be realized (Höjer and Mattsson 2000; Quist 2013; Robinson 1988). Among the many advantages of employing backcasting is its capability to calculate the cost of investments, such as energy infrastructure, necessary to achieve the visionary future. Backcasting scenarios address the question, *what would need to happen to achieve a specific end state?* (Quist 2013).

A number of new backcasting studies examine "deep decarbonization" futures, which refer to the reduction of GHG emissions over time to a level consistent with limiting global warming to 2°C or less. There is extensive development of global-scale energy-environment modeling for this purpose (for a brief review, see Fawcett et al., 2014b). More recently, a body of literature also has emerged on scenario pathways consistent with a 1.5°C world (Kriegler et al., 2018; Millar et al., 2017; Rogelj et al., 2015, 2018; Su et al., 2017). There also are a significant number of studies arguing that it is possible for the United States, and the world, to significantly reduce carbon emissions by 2050 (Delucchi and Jacobson 2011; Fthenakis et al., 2009; IPCC 2011; Jacobson and Delucchi 2011; Jacobson et al., 2015; MacDonald et al., 2016; NREL 2012; Mai et al., 2014).[18] This chapter focuses on a select number of studies in North American economies with visions of a 2°C future using multiple technologies. These scenarios include those from 1) the Deep Decarbonization Pathways Project (2015; DDPP); and 2) the White House (2016) *Mid-Century Strategy* report.

The DDPP is a collaborative global initiative of the United Nations Sustainable Development Solutions Network (UNSDSN) and Institute for Sustainable Development and International Relations (IDDRI). Each of the 16 countries participating in the project explores how an individual nation can transform its energy systems by 2050 to limit the anthropogenic increase in global mean surface temperature to less than 2°C. Deep decarbonization pathways focus on a wide range of important actions, although three appear most important to the energy system: 1) high energy efficiencies across all sectors; 2) electrification wherever possible, with nearly complete decarbonization of the electricity system; and 3) reduced carbon in other kinds of fuels (Deep Decarbonization Pathways Project 2015). Included in this review are scenarios from Canada, Mexico, and the United States, each of which is engaged in its own scenario exercises and that are not official governmental exercises.

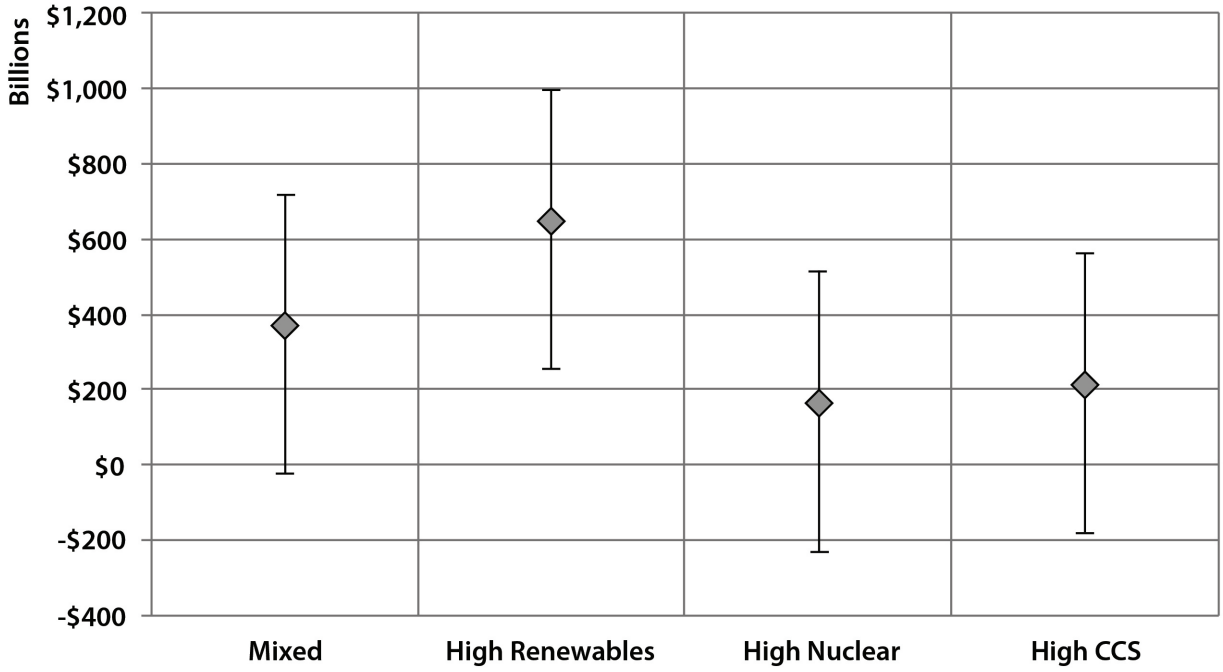
[18] A debate has emerged in this literature concerning the portfolio of clean energy technologies and energy carriers necessary for the transformation (see for example, Clack et al., 2017).

The Canadian DDPP examines major shifts in technology adoption, energy use, and economic structure that are consistent with continued economic and population growth and a nearly 90% reduction in national GHG emissions from 2010 levels by 2050 (Bataille et al., 2014, 2015). In the reference case, national emissions are relatively stable over the forecast period, reaching 201 Tg C in 2050 (181.6 Tg C of energy emissions) with the net impact of higher oil prices and a production increase of 13 Tg C (7%) by 2050. The Canadian deep decarbonization pathway achieves an overall GHG emissions reduction of nearly 90% (178 Tg C) from 2010 levels by 2050, while maintaining strong economic growth. Over this period, GDP rises from $1.26 trillion to $3.81 trillion (US$ 2010), a tripling of Canada's economy. The reduction in emissions is driven most significantly by a reduction in the carbon intensity of energy use, as renewables and biomass become the dominant energy sources and there is broad fuel switching across the economy toward electricity and biofuels. Electricity production nearly completely decarbonizes. Overall, the carbon intensity of Canada's total primary energy supply declines by 90% between 2010 and 2050. This result is robust across different technology scenarios. For example, if biofuels are not viable, transportation could transition to increased use of electricity generated with renewables and fossil fuels with CCS, especially if better batteries become available. If CCS processes are not available, the electricity sector could decarbonize using more renewables and nuclear. End-use energy consumption rises by only 17% over this period, compared to a 203% increase in GDP. This difference is due both to structural changes in the economy and to increases in energy efficiency.

The costs of these transformations include significant restructuring of energy investments. The study found that overall incremental investment increases by around $13.2 billion (CAD$ 2014) annually (8% increase relative to historic levels), but this average increase hides sectoral differences. Consumers spend $3.0 billion (CAD$ 2014) less each year on durable goods like refrigerators, cars, appliances, and houses, while firms must spend $16.2 billion (CAD$ 2014) more. Approximately $13.5 billion (CAD$ 2014) of costs are in the electricity sector (+89% over historical levels), by far the most important shift, and $2.9 billion (CAD$ 2014) are in the fossil fuel extraction sector for the adoption of advanced low-emissions technologies such as CCS, solvent extraction, and direct-contact steam generation (+6% over historical levels) (Bataille et al., 2015).

For Mexico, the future analysis was to provide preliminary deep decarbonization routes to determine whether there are general conclusions that can be drawn at an aggregate level. The scenarios sought economic development that is low–carbon, rather than unconditional decarbonization. Therefore, Mexico's deep decarbonization project aimed to reduce GHG emissions to 50% below 2000 levels by 2050 (a target of approximately 71 Tg C), in accordance with the target set by the General Climate Change Law of 2012. The reference scenario used by the project, based on current trends and well-informed assumptions of future activity for the main drivers of CO_2 emissions, predicted emissions could reach 246 Tg C by 2050. The central deep decarbonization scenario suggests that total CO_2 emissions could reach 68.2 Tg C by 2050, including fugitive and process emissions (a 51% decline from 2000 levels), largely induced by declines in energy intensity of 59% and declines in CO_2 intensity of 66%. Final energy consumption in 2050 reaches 8.1 EJ, 35% less than in the reference trajectory, although it is an increase of 38% compared with the 2010 levels of 5.9 EJ. Costs of the transformation were not calculated. These reductions were plausible under certain assumptions, such as accelerated increases in energy-efficiency uptake across all sectors; rapid development and deployment of CCS; zero-emissions vehicles; energy-storage technologies; smart transmission and distribution (smart grids); and system flexibility to promote, adopt, and combine diverse options over the time frame of decarbonization (Tovilla and Buira 2015[eds.]).

For the U.S. DDPP, the vision is to achieve an 80% GHG reduction below 1990 levels by 2050,



Note: The error bars in this figure show the 25th and 75th percentile values.

Figure 3.13. Incremental Energy System Costs in 2050. Error bars show the 25% and 75% values. Key: CCS, carbon capture and storage. [Figure source: Redrawn from Williams et al., 2014, used with permission.]

and DDPP uses multiple pathways to achieve these reductions through existing commercial or near-commercial technologies (Williams et al., 2014, 2015). The three pillars of decarbonization across all pathways are high-efficiency end use of energy in buildings, transportation, and industry; nearly complete decarbonization of electricity; and reduced carbon in fuels and electricity production. Pathways were named "High renewables," "High nuclear," "High carbon capture and storage," and "Mixed," based on the dominant strategy used for energy generation and carbon mitigation. The goal of the pathways was to reduce total GHG emissions from a net of around 1,470 Tg C and energy emissions of 1,390 Tg C to overall net GHG emissions of no more than 300 Tg C and fossil fuel combustion emissions of no more than 205 Tg C. To achieve this outcome, the vision includes a reduction of petroleum consumption by 76% to 91% by 2050 across all scenarios. The study finds that all scenarios met the target, demonstrating robustness by showing the existence of redundant technology pathways to deep decarbonization.

The costs of the transformation include incremental energy system costs (i.e., incremental capital costs plus net energy costs). These are defined by costs of producing, distributing, and consuming energy in a decarbonized energy system relative to that of a reference case system based on the EIA (2013c) report as a metric to assess the costs of deep reductions in energy-related CO_2 emissions. Based on an uncertainty analysis of key cost parameters in the four analyzed cases, the 25% to 75% range extends from negative $90 billion to $730 billion (US$ 2012) in 2050 (see Figure 3.13, this page). The median costs value is just over $300 billion (US$ 2012). This median estimate of net energy system costs is 0.8% of U.S. GDP in 2050, with a 50% probability of costs falling between –0.2% and 1.8% of GDP. Uncertainty in costs is due to assumptions about consumption

levels, technology costs, and fossil fuel prices nearly 40 years into the future. The higher end of the probability distribution (75% estimate of $730 billion) assumes little to no technology innovation over the next four decades. The overall costs of deeply decarbonizing the energy system is dominated by the incremental capital cost of low-carbon technologies in power generation, light- and heavy-duty vehicles, building the energy system, and industrial equipment. The U.S. DDPP result of total mitigation costs of $1 trillion to $2 trillion through 2050 is consistent with the EMF24 study (Williams et al., 2015).

The report suggests that the transition to a deeply decarbonized society would not require major changes in individual energy use because the scenarios were developed to support the same level of energy services and economic growth as the references case of EIA (2013c). For example, Americans would not be required to use bicycles in lieu of cars, eat purely vegetarian diets, or wear sweaters to reduce home heating loads (Williams et al., 2015).

The aforementioned White House (2016) *Mid-Century Strategy* (MCS) report charts pathways for the United States consistent with a reduction of 80% or more (relative to 2005 levels) by 2050. The MCS goal reduces annual emissions from around 1,609 Tg C in 2005 to 410 Tg C in 2050. The ensemble of scenarios used differs in regard to the reliance on key low-carbon technologies and decarbonization strategies. Three sets of MCS scenarios are 1) "MCS benchmark," which assumes continued innovation spurred by decarbonization policies and current levels of RD&D funding; 2) "Negative emissions," two alternative scenarios that explore the implications of achieving different levels of negative emissions such as no CO_2 removal technology and limited sink scenarios; and 3) "Energy technology," which comprises three scenarios that explore challenges and opportunities associated with the low-carbon energy transition: no CCS, smart growth, and limited biomass scenarios.

The study findings suggest that by 2050 energy efficiency can reduce primary energy use by over 20% from 2005 levels and that nearly all fossil fuel electricity production can be replaced by low-carbon technologies, including renewables, nuclear, and fossil fuels or bioenergy combined with CCS. Furthermore, the study argues that there are opportunities to expand electrification into the transportation, industrial, and buildings sectors, reducing their direct fossil fuel use by 63%, 55%, and 58%, respectively, from 2005 to 2050. Reaching the MCS goal requires a substantial shift in resources away from GHG-intensive activities, including increasing annual average investments in electricity-generating capacity to between 0.4% and 0.6% of U.S. GDP.

In summary, the backcasting exercises for North America and the United States suggest that reaching a goal of 80% reductions in GHG emissions (relative to 2005 levels) is plausible, although achieving the goal will require both policies and technological advances. The incremental cost of mitigation for the United States was identified as between 0.4% to 0.8% of annual GDP (Williams et al., 2014) and an annual incremental cost of $13.2 billion (CAD$ 2014) for Canada. The final numbers are comparable with the $1.5 trillion to $2.0 trillion costs identified by the Edison Electric Institute (2008) for infrastructure investments necessary to 2030 for upgrading the electricity system.

There are significant caveats to these results. Previously mentioned mitigation costs do not include direct benefits (e.g., avoidance of infrastructure damage) and co-benefits (e.g., avoided human health impacts from air pollution) of emissions reductions. These benefits and co-benefits can be substantial. For example, U.S. EPA (2015a, 2017b) estimated some of the benefits and co-benefits of climate mitigation through 2100 for the United States. In their most recent report (U.S. EPA 2017b), the agency examined 22 issue areas across the human health, infrastructure, electricity, water resources, agriculture, and ecosystems sectors. Annual cost estimates for these sectors due to climate change during the year 2050 were $170 billion and $206 billion (US$ 2015) under Representative Concentration Pathway (RCP) 4.5 and RCP8.5 conditions, respectively. By 2100, costs in these sectors due to climate change were estimated at $356 billion and $513 billion

annually (US$ 2015) under RCP4.5 and RCP8.5 conditions, respectively (U.S. EPA 2017a).

The benefits and co-benefits of mitigation may be even larger than estimated. U.S. EPA (2017b) noted that its report estimates did not include some health effects (e.g., mortality due to extreme events other than heat waves, food safety and nutrition, and mental health and behavioral outcomes); effects on ecosystems (e.g., changes in marine fisheries, impacts on specialty crops and livestock, and species migration and distribution); and social impacts (e.g., national security and violence). Other estimates at the global scale, include damages (in terms of reduced consumption) from business-as-usual scenarios (resulting in up to a 4°C warming by 2100) that range from 1% to 5% of the global GDP, incurred every year (Norhaus 2013). Costs may be even higher if temperatures continue to rise, with potential reductions of 23% of global incomes and widening global income inequality by 2100 (Burke et al., 2015a).

Additionally, the costs to mitigate may be lower than reported depending on when they appear. For example, in some studies, the majority of energy mitigation costs are incurred after 2030, as deployment of low-carbon infrastructure expands. Technology improvements and market transformation over the next decades, however, could significantly reduce these expected costs. Also important, as mentioned previously in this report, is that CO_2 removal technologies such as CCS; carbon capture, utilization, and storage (CCUS); and BECCS are not currently deployed at scale, as many of the listed scenarios mentioned. Nuclear power expansion, as envisioned in some scenarios, also faces technical and political challenges (see Box 3.2, Potential for Nuclear Power in North America, p. 120).

The changing climate also may affect energy supply and use in a variety of ways, and adapting to these changes will create future North American energy systems that differ from those of today in uncertain ways (Dell et al., 2014). While the trajectories from the outlined scenarios are "plausible," whether any of them are "feasible" depends on a number of subjective assessments such as whether Canada, Mexico, and the United States at this time or any time in the future would be willing to make the necessary transformations and how future climate change will transform both opportunities and risks (Clarke et al., 2014; Dell et al., 2014).

3.9 Synthesis, Knowledge Gaps, and Key Challenges

The North American energy system is a net source of carbon emissions to the atmosphere. Recently, however, this system has undergone dramatic changes. Since 2007, energy use and CO_2e emissions have decreased despite population and GDP per capita increases. This decrease accompanied a regional transition to greater reliance on natural gas energy sources and an increase in deployed renewable energy capacity. Early in the economic recession of 2007 to 2008, most of the decreases in energy use and CO_2e emissions were due to changes in behavior, including a slowdown in the consumption of goods and services. However, post-recession, a number of other factors have emerged that have kept emissions levels low. Growing energy efficiency and changes in regional carbon intensity were observed across all energy sectors, facilitated by new technologies and changes in the fuel mixture, particularly the increase in natural gas and renewables and the decrease in coal for electricity production, as well as industrial processes and a variety of lower carbon–intensity technologies. These dynamics have been influenced by relative changes in the price of fuels, slow growth in electricity demand, the growing importance of electricity demand for electronics, and a history of policies that promoted technology development for energy efficiency and clean energy. In Mexico, the recent *Reforma Energética* and strong leadership on environmental issues underpin energy restructuring that is prompting changes in energy use, energy intensity, and that nation's fuel mix. Across North America, state and subnational governments are increasingly involved in carbon management decisions. The result of all

these influences has been a decline in CO_2e emissions and a restructuring of the North American energy system.

Whether this trend will continue depends on both the continuation of energy system change and energy and economic policies. Furthermore, despite the decrease in GHG emissions experienced over the recent past and the recent decoupling of emissions from economic growth, all studies suggest that further efforts are needed to meet the 2°C trajectory and that these added reductions can come about only with policy intervention. Key methods for lowering carbon emissions from the North American energy system include 1) increasing energy efficiency across all sectors; 2) upgrading, modernizing, and standardizing the aging energy infrastructure; 3) reducing the use of carbon-intensive fuels and technologies; 4) transitioning to low-carbon energy sources and further developing scalable carbon sink technologies; and 5) generating public acceptance and policy effectiveness for decarbonization, whether at the national or subnational levels. In general, whether the current patterns in energy use and carbon emissions will follow historical trends and rebound to higher levels than 2007 by the early 2020s, or whether the restructuring of the energy system currently underway will be enough to change the energy use and CO_2e emissions pathways, remains an open question. Notwithstanding these uncertainties, studies suggest policy change and infrastructure investment across a wide variety of technologies can put the North American energy system on a 2°C trajectory by 2050 (80% reduction in emissions relative to 2005 levels). The costs of energy system changes in the United States are estimated to be around $1 trillion to $4 trillion by 2050, with this investment offsetting some or all of expected costs without mitigation of approximately US$170 billion and $206 billion (US$ 2015) annually by 2050.

Much is already understood about the North American energy system and its role in the carbon cycle, but significant knowledge gaps remain. Most importantly, four areas stand out that need further examination and research. First, the governance and institutional needs in the transition to a low-carbon society are not well understood. As identified herein, studies have examined the potential costs of mitigation, but much more detail is needed on the governance structures and institutions required to support navigation through the future energy transition. Second, the potential feedbacks associated with changes in the energy system in combination with climate change, exogenous and endogenous system changes, and the impacts of those feedbacks on the energy system are not clear. Third, studies have identified the potential extent of CH_4 emissions from natural gas extraction and use, putting into question the role of natural gas as a "bridge fuel." Also, the amount of gas that escapes as leakage and fugitive emissions has yet to be measured accurately. The effectiveness of policies that increase energy efficiencies, reduce carbon intensity, and reduce emissions, while also maintaining social benefits such as environmental equity and economic growth, needs to be more fully documented. Finally, detailed comparable data for end-use energy, emissions, and projections across North American economies have yet to be compiled, and, as noted, end-use data across economies differ due to a number of factors, and thus better data could help inform evidenced-based regional policies regarding carbon management.

The North American energy system, although varied across economies, has developed into a vast, complex infrastructure and set of institutional arrangements that have consistently provided for the economic growth and well-being of the regional population. Yet, the workings of this system contribute significantly to the carbon cycle. This system may be able to continue to provide the reliable and consistent energy demanded by increasing regional activities with decreasing contributions of CO_2e to the atmosphere in the near future. Research suggests that the emissions-level targets that secure populations from predicted impacts of climate change and the potential impacts of energy system internal change cannot be met in the absence of policy drivers.

SUPPORTING EVIDENCE

KEY FINDING 1

In 2013, primary energy use in North America exceeded 125 exajoules (EJ), of which Canada was responsible for 11.9%, Mexico 6.5%, and the United States 81.6%. Of total primary energy sources, approximately 81% was from fossil fuels, which contributed to carbon dioxide equivalent (CO_2e) emissions levels, exceeding 1.76 petagrams of carbon, or about 20% of the global total for energy-related activities. Of these emissions, coal accounted for 28%, oil 44%, and natural gas 28% (*very high confidence, likely*).

Description of evidence base

Data on energy use are collected by the U.S. Department of Energy's (U.S. DOE) Energy Information Administration (EIA) and the Organisation for Economic Cooperation and Development's (OECD) International Energy Agency (IEA). Data for CO_2e were accessed from a number of sources, including the EIA, IEA, U.S. DOE Carbon Dioxide Information Analysis Center (CDIAC) database (Boden et al., 2016), and the World Resources Institute (WRI) CAIT database (cait.wri.org). All data suggest similar trends, although the exact values differ.

Major uncertainties

These datasets include uncertainties related to the amount of fossil fuel used (i.e., typically identified through sales-weighted averages to create a national average) and the carbon and heat contents of the energy reserve (e.g., U.S. EPA 2017a). According to the literature, there are further uncertainties related to lost and fugitive emissions (Alvarez et al., 2012; Brandt et al., 2014; Karion et al., 2013; Pétron et al., 2014; Zavala-Araiza et al., 2015). Estimates of fugitive methane (CH_4) levels indicate that these emissions are unlikely to substantially alter Key Finding 1 (Alvarez et al., 2012; Brandt et al., 2014). Fugitive CH_4 from oil, gas, and coal production and transportation is included in the U.S. Environmental Protection Agency (U.S. EPA), U.S. DOE, Canadian, and Mexican inventories, but there may be further emissions not yet accounted. Furthermore, while the trends are consistent across data sources, the absolute values of greenhouse gas (GHG) emissions levels from energy consumption and production vary across datasets because of differences in system boundary definitions, inclusion of industrial process emissions, emissions factors applied, and other issues.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is very high confidence in the likelihood that the statement is based on consistent findings across the literature.

Summary sentence or paragraph that integrates the above information

For Key Finding 1, there is incontrovertible evidence that North American energy use and CO_2e emissions have dropped over the past 10 years, specifically since 2007.

KEY FINDING 2

North American energy-related CO_2e emissions have declined at an average rate of about 1% per year, or about 19.4 teragrams CO_2e, from 2003 to 2014 (*very high confidence*).

Description of evidence base

Data on CO_2e emissions are calculated by the EIA, IEA, and CDIAC databases (Boden et al., 2016) and by the WRI CAIT database (*cait.wri.org*). All data suggest similar trends, although the exact values differ. Key Finding 2 is consistent across these sources.

Major uncertainties

These datasets include uncertainties related to the amount of fossil fuel used (typically identified through sales-weighted averages to create a national average) and the carbon and heat contents of the energy reserve (e.g., see U.S. EPA 2017a, Annex 2). According to the literature, there are further uncertainties related to lost and fugitive emissions (Alvarez et al., 2012; Brandt et al., 2014; Karion et al., 2013; Pétron et al., 2014; Zavala-Araiza et al., 2015). Estimates of fugitive CH_4 levels indicate that these emissions are unlikely to substantially alter Key Finding 2 (Alvarez et al., 2012; Brandt et al., 2014). Fugitive CH_4 from oil, gas, and coal production and transportation is included in U.S EPA and DOE and Canadian and Mexican inventories, but there may be further emissions that are not yet accounted. For U.S. DOE, fugitive emissions include the unintended leaks of gas from the processing, transmission, and transportation of fossil fuels. Furthermore, while the trends are consistent across data sources, the absolute values of GHG emissions levels from energy consumption and production vary across datasets because of differences in system boundary definitions, inclusion of industrial process emissions, emissions factors applied, and other issues.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is very high confidence in the likelihood that the statement is based on consistent findings across the data sources assessed.

Estimated likelihood of impact or consequence, including short description of basis of estimate

It is not appropriate to reflect on the likelihood of impacts of these trends without longer time series demonstrating that North American and international energy and industrial GHG emissions continue to decline. The total effect of energy and industrial GHG emissions on atmospheric GHG concentrations and climate change depends on total international emissions and future GHG emissions trajectories.

Summary sentence or paragraph that integrates the above information

Key Finding 2 that North American energy and industrial GHG emissions have declined since 2007 is supported by multiple datasets, with total uncertainty surrounding fugitive CH_4 and various emissions calculation approaches unlikely to alter this finding.

KEY FINDING 3

The shifts in North American energy use and CO_2e emissions have been driven by factors such as 1) lower energy use, initially as a response to the global financial crisis of 2007 to 2008 (*high confidence, very likely*); but increasingly due to 2) greater energy efficiency, which has reduced the regional energy intensity of economic production by about 1.5% annually from 2004 to 2013, enabling economic growth while lowering energy CO_2e emissions. Energy intensity has fallen annually by 1.6% in the United States and 1.5% in Canada (*very high confidence, very likely*). Futher factors driving lower carbon intensities include 3) increased renewable energy production (up 220 petajoules [PJ] annually from 2004 to 2013, translating to an 11% annual average increase in renewables) (*high confidence, very likely*); 4) a shift to natural gas from coal sources for industrial and electricity production (*high confidence, likely*); and 5) a wide range of new technologies, including, for example, alternative fuel vehicles (*high confidence, likely*).

Description of evidence base

Over the past decade, Key Finding 3 found that annual energy intensity dropped 1.5% in Canada, 0.04% in Mexico, and 1.6% in the United States. In the United States, gross domestic product (GDP) has grown by more than 10% from 2008 to 2015, while fossil fuel combustion CO_2 emissions declined 6% from 2008 to 2014. Canada's GDP grew by 11% from 2008 to 2015, while its energy-related CO_2 emissions grew roughly 2% from 2008 to 2014. In Mexico, GDP grew 15% between 2008 and 2015, and energy-related CO_2 emissions remained relatively flat, with a 0.3% decrease from 2008 to 2014 (IEA 2016a; IMF 2016).

Economic structural changes have contributed to some of this decline, with more of North American manufacturing occurring overseas, especially in East Asian countries. From 2004 to 2014, the United States exhibited net offshoring every year except for 2011 (Kearney 2015). More recently, there were reports of reshoring to the United States, although there is uncertainty in whether this will exceed or even break even with continued offshoring (Sirkin et al., 2011; Tate 2014). Today, a trend of nearshoring is projected as manufacturing costs in China rise and companies move their operations to Mexico (Kitroeff 2016; Priddle and Snavely 2015).

North American renewable energy production has increased over the past 10 years. For electricity, nonhydropower renewables, including wind, solar, and biomass, have increased from 2.4% in 2004 to 6.1% in 2013. This translates into a 10.6% annual average increase, adding approximately 220 PJ of renewable energy into the North American electricity system annually (EIA 2016c).

A large portion of Canada's 80% of nonfossil power generation comes from hydropower, while in the United States and Mexico nonfossil power contributes 32% and 22%, respectively, largely from nuclear. In total, carbon-free power sources contribute 38% of North American energy generation (EIA 2016c).

Major uncertainties

As with other contributing factors to energy and industrial emissions reductions, there is some uncertainty regarding the contribution of reduced energy intensity to emissions reductions. Kotchen and Mansur (2016) estimate reduced energy intensity contributed 6% of U.S. emissions reductions from 2007 to 2013.

The largest uncertainty surrounds the trajectory of carbon-free energy deployment in North America, which likely will depend heavily on policies that continue to incentivize lower-carbon forms of energy relative to fossil fuels. The declining cost of renewable and nonfossil technologies have made them cost-competitive with fossil fuels in some but not all regions of North America, and the future trajectories of technology cost reductions also are uncertain and dependent on public and private investment in research, development, and demonstration.

Although renewable energy deployment has been recognized as a contributing factor to GHG emissions reductions in North America, the precise scale of influence has been debated. The global financial crisis and natural gas deployment are likely to have had a larger effect than renewable energy in reducing North American energy emissions during 2007 to 2009 (Feng et al., 2015; Gold 2013; U.S. DOE 2015a), but, subsequently, changes in the energy system (including the increase in renewable energy and decrease in energy intensities) have helped to continue the trend.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is very high confidence in the finding based on the results of official data.

Estimated likelihood of impact or consequence, including short description of basis of estimate

Reductions in the energy intensity of economic output are very likely to be based on structural economic changes that will have lasting effects in reducing the GHG emissions from economic growth. The exception is whether "reshoring" occurs (i.e., the transfer of a business operation that had moved overseas or out of its originating country back to the country where it was originally relocated).

Increasing renewable and nuclear energy technology deployment is likely to continue based on existing and planned policies in North American countries, as well as market and technology cost trends. Increasing deployment of these technologies would have significant impacts on energy and industrial GHG emissions.

Summary sentence or paragraph that integrates the above information

In Key Finding 3, reduced energy intensity of economic output in North America is allowing for reduced energy-related GHG emissions even as the three North American economies recover from the 2007 to 2008 recession. These trends very likely reflect structural economic changes that would have a lasting effect on energy-related GHG emissions into the future and may represent a departure from the typical rebounding cycles experienced previously.

Although still a relatively small share of its energy mix, North America increased renewable energy production by about 220 PJ annually from 2004 to 2013, translating to a 10.6% annual average increase. In 2013, nonhydropower renewable fuels reached 3.25 EJ but accounted for about 6.1% of total electricity generation. Hydropower and nonfossil nuclear power sources remain the most important low-carbon energy generators, accounting for 31.7% of total electricity generation.

Renewable energy and nuclear energy technologies are a small but growing portion of the North American energy sector and are likely to have an ongoing effect in reducing energy and industrial emissions if policy, market, and technology trends hold.

KEY FINDING 4

A wide range of plausible futures exists for the North American energy system in regard to carbon emissions. Forecasts to 2040, based on current policies and technologies, suggest a range of carbon emissions levels from an increase of over 10% to a decrease of over 14% (from 2015 carbon emissions levels). Exploratory and backcasting approaches suggest that the North American energy system emissions will not decrease by more than 13% (compared with 2015 levels) without both technological advances and changes in policy. For the United States, however, decreases in emissions could plausibly meet a national contribution to a global pathway consistent with a target of warming to 2°C at a cumulative cost of $1 trillion to $4 trillion (US$ 2005).

Description of evidence base

Key Finding 4 is based on results from three different types of energy scenarios, including five projections (United States from EIA, Canada from Environment and Climate Change Canada, Mexico from IEA, and private firms BP and ExxonMobil); exploratory scenarios from Royal Dutch Shell, the World Energy Council, and the Pew Center on Global Climate Change; and backcasting scenarios from the Deep Decarbonization Pathways Project (for the United States, Canada, and Mexico), the Energy Modeling Forum (i.e., includes approximately nine different modeling groups), and the U.S. government. The statement on mitigation costs ("US$107 and $206 billion (US$ 2015) annually") is from the findings of a report by U.S. EPA (2017b).

Major uncertainties

There are significant incalculable uncertainties for futures studies. Therefore, no certainties, qualitative or quantitative, have been provided.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

With high confidence, the literature that forecasts carbon trajectories agrees generally with the outcome of the review provided.

Estimated likelihood of impact or consequence, including short description of basis of estimate

The provision of future studies is for decision making. The scenario data provide enough information for a discussion of how to mitigate carbon emissions.

Summary sentence or paragraph that integrates the above information

There are a variety of carbon futures for the North American energy system. They include higher and much lower emissions levels, depending on both current trends and potential future uses of technologies. Importantly, achieving significantly lower emissions in the near future will depend on policy, without which it will not be achieved.

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4 Understanding Urban Carbon Fluxes

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KEY FINDINGS

1. Urban areas in North America are the primary source of anthropogenic carbon emissions, with cities responsible for a large proportion of direct emissions. These areas are also indirect sources of carbon through the emissions embedded in goods and services produced outside city boundaries for consumption by urban dwellers (*medium confidence, likely*).

2. Many societal factors drive urban carbon emissions, but the urban built environment and the regulations and policies shaping urban form (e.g., land use) and technology (e.g., modes of transportation) play crucial roles. Such societal drivers can lock in dependence on fossil fuels in the absence of major technological, institutional, and behavioral change. Some fossil fuel–related infrastructure can have lifetimes of up to 50 years (*high confidence*).

3. Key challenges for urban carbon flux studies are observational design, integration, uncertainty quantification, and reconciliation of the multiple carbon flux approaches to detect trends and inform emissions mitigation efforts (*medium confidence, likely*).

4. Improvements in air quality and human health and the reduction of the urban heat island are important co-benefits of urban carbon emissions mitigation (*high confidence, very likely*).

5. Urban methane (CH_4) emissions have been poorly characterized, but the combination of improved instrumentation, modeling tools, and heightened interest in the problem is defining the range of emissions rates and source composition as well as highlighting infrastructure characteristics that affect CH_4 emissions (*high confidence*).

6. Urban areas are important sites for policymaking and decision making that shape carbon fluxes and mitigation. However, cities also are constrained by other levels of government, variations in their sources of authority and autonomy, capacity, competing local priorities, and available fiscal resources (*high confidence*).

Note: Confidence levels are provided as appropriate for quantitative, but not qualitative, Key Findings and statements.

4.1 Introduction

Urban areas are concentrated domains of carbon fluxes because of the sheer magnitude of 1) urban populations; 2) economic activities; and 3) the fossil fuel–based energy, goods, and services on which these areas currently depend. Though sensitive to the urban boundary definition chosen and the accounting framework adopted (production versus consumption), carbon fluxes resulting from urban activities are estimated to be responsible for up to 80% of the total North American anthropogenic flux of carbon dioxide (CO_2) to the atmosphere (Jones and Kammen 2014; Seto et al., 2014). Per capita energy consumption in U.S. urban areas is estimated to be 13% to 16% less than the national average, and consumption varies more widely across cities than in rural areas (Parshall et al., 2010; see Figure 4.1, p. 191). This concentrated source of carbon emissions is dominated by the combustion of fossil fuels (see Ch. 3: Energy Systems, p. 110, for a detailed treatment of carbon emissions associated with energy systems). However, other direct fluxes include carbon exchanged by the urban biosphere, methane (CH_4) emissions from leaking infrastructure, anaerobic decomposition (e.g., landfills and wastewater treatment), and human respiration. Cities are also responsible for large indirect fluxes via the demand for goods and services that are produced elsewhere. Understanding urban carbon fluxes is essential to understanding the spatiotemporal distribution of global anthropogenic carbon flux, the forces driving fossil fuel–based consumption,

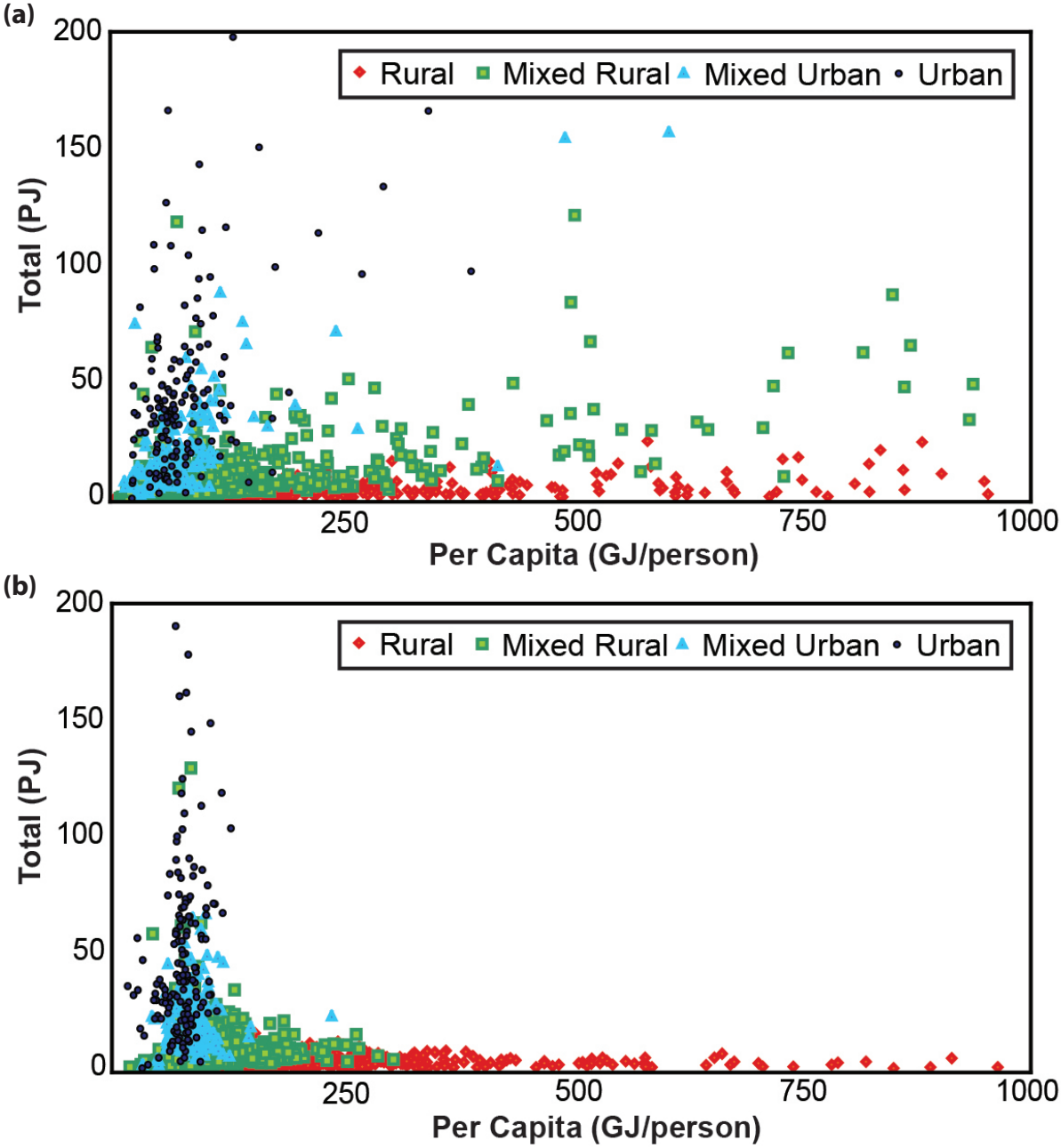

Figure 4.1. Per Capita Energy Consumption Versus Total Energy Consumption in Rural to Urban U.S. Counties. (a) Direct energy consumption measured in petajoules (PJ) and gigajoules (GJ) in building and industry and **(b)** direct energy consumption for transportation. [Figure source: Reprinted from Parshall et al., 2010, copyright Elsevier, used with permission.]

and the policy options available to cities in their role as innovators in emissions mitigation. This chapter aims to assess this understanding.

The current understanding of carbon fluxes from urban areas has improved considerably since the *First State of the Carbon Cycle Report* (SOCCR1;

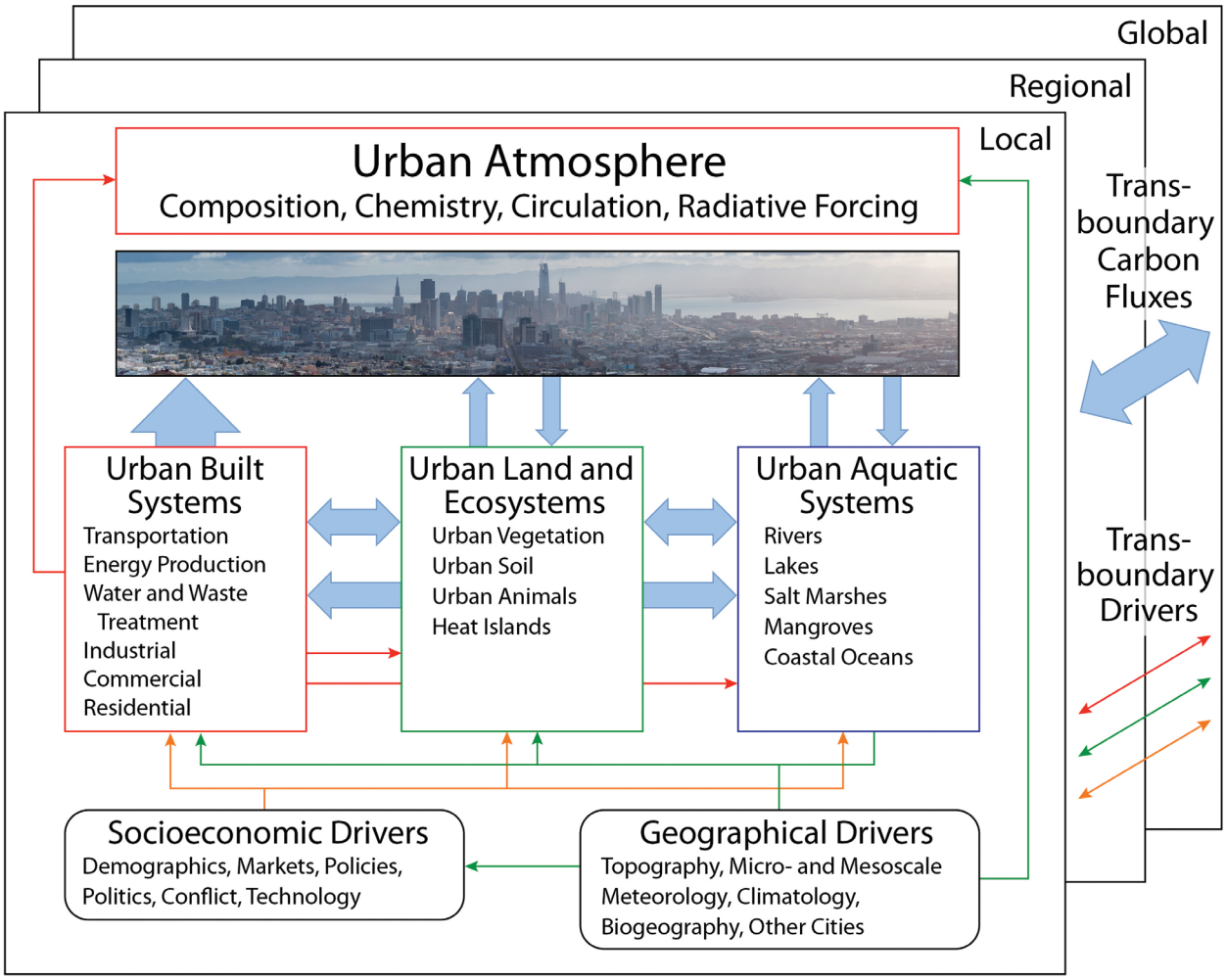

Figure 4.2. Key Components of Urban Carbon Cycling. Major reservoirs and processes (colored boxes) are depicted, along with carbon (C) emission and removal fluxes (blue block arrows), major drivers (oval boxes), and examples of process linkages (colored thin arrows). Outer boxes depict the relationships among local, regional, and global carbon through transboundary (lateral) carbon fluxes as well as interconnected drivers (e.g., socioeconomic, geographical, and built systems). [Figure source: Redrawn from Hutyra et al., 2014, used with permission under a Creative Commons license (CC-BY-NC-ND 3.0).]

CCSP 2007). Numerous urban carbon flux studies have been completed, and long-term research aimed at understanding aspects of urban carbon flows, drivers, and policy dimensions continues in some cities. Though often challenging to integrate, the growing number of studies within the North American urban domain are helping to improve understanding and establish new scientific knowledge and application to policymaking (Chester et al., 2014; Gurney et al., 2015; Hutyra et al., 2014; Marcotullio et al., 2014; Romero-Lankao et al., 2014).

Carbon flux differences within and across urban areas are more complex than the sum of populations, reflecting complex relationships among consumption, technology, infrastructure, economics, and behavior and lifestyle (see Figure 4.2, this page; Lenzen and Peters 2009; Lenzen et al., 2008; Seto et al., 2014). A key component of urban

carbon emissions, and a driver of future trends, is the interaction between human activity and the built environment, which includes large infrastructural systems such as buildings, roads, and factories. One need is to explore how urban infrastructure and morphology will influence current and future energy consumption and development (Creutzig et al., 2016; Müller et al., 2013; Salat and Bourdic 2012; Schiller 2007; Tanikawa and Hashimoto 2009).

The emerging role of subnational and transnational organizations and stakeholders within international policymaking, combined with the dominance of urban carbon emissions, has brought mitigation of carbon emissions from cities into consideration (Hsu et al., 2015; Rosenzweig et al., 2010, 2016; Wang 2012). Carbon mitigation approaches in North American cities vary widely due to a number of factors such as the urban economic profile, local policy initiatives, climate, and interactions with other governance levels (Homsy and Warner 2014; Krause 2012; Markolf et al., 2017; Sharp et al., 2010; Zahran et al., 2008). The impact of local policies on carbon emissions often is not monitored or assessed (Bulkeley 2010; Portney 2013), nor are the drivers for carbon mitigation policies systematically understood. Thus, causal links between policy and atmospheric effects are not always well known and may be unique to the city (Hughes 2017). Critically, urban emissions mitigation opportunities are often dependent upon or limited by interaction with governance at county, state, or provincial scales, emphasizing a need to better understand these relationships within the context of climate policy. For a better understanding of the societal drivers, further research is necessary on the interrelated environmental costs, benefits, constraints, and opportunities of different approaches within North American cities.

4.2 Current Understanding of Carbon Fluxes and Stocks

4.2.1 Accounting Framework and Methods

Many urban researchers, using a spectrum of methodological frameworks and measurement approaches, have quantified urban carbon flows and stocks in North American cities. The accounting framework determines the meaning and application of urban carbon flux information. Broadly speaking, two frameworks have been used: accounting for direct fluxes only or accounting that also includes indirect fluxes occurring outside the chosen urban area but driven by activities within it (Gurney 2014; Ibrahim et al., 2012; Wright et al., 2011). The former, also variously referred to as "production-based" or "in-boundary" accounting, quantifies all direct carbon flux between the Earth's surface and the atmosphere within the geographic boundaries of the urban area of study (Chavez and Ramaswami 2011; Ramaswami and Chavez 2013; Wright et al., 2011). In-boundary accounting also is aligned with "scope 1" flux, a term emanating from carbon footprinting of manufacturing supply chains (WRI/WBCSD 2004). This framework will include within-city combustion of fossil fuels, exchange of carbon with vegetation and soils, absorption by concrete, human respiration, anaerobic decomposition, and CH_4 leaks. An in-boundary accounting framework often is favored for integration with atmospheric measurements, which also can be used to estimate surface-to-atmosphere fluxes within the chosen geographical domain (Lauvaux et al., 2016).

Indirect fluxes include those associated with energy used to create or deliver electricity, products, or services consumed in a given urban area or the carbon flux associated with waste decay or removal of material to the waste stream (Minx et al., 2009; Mohareb and Kennedy 2012). These fluxes include consumption-based flow of products manufactured outside the consuming city (see Figure 4.3, p. 194). A study of eight cities found that the urban carbon footprint increased by an average of 47% when indirect fluxes were included (Hillman and Ramaswami 2010). Quantification of indirect fluxes typically employs a life cycle assessment framework and also can quantify the carbon stock residing in urban infrastructure or materials (Churkina et al., 2010; Fraser and Chester 2016; Hammond and Jones 2008; Lenzen 2014; Reyna and Chester 2015).

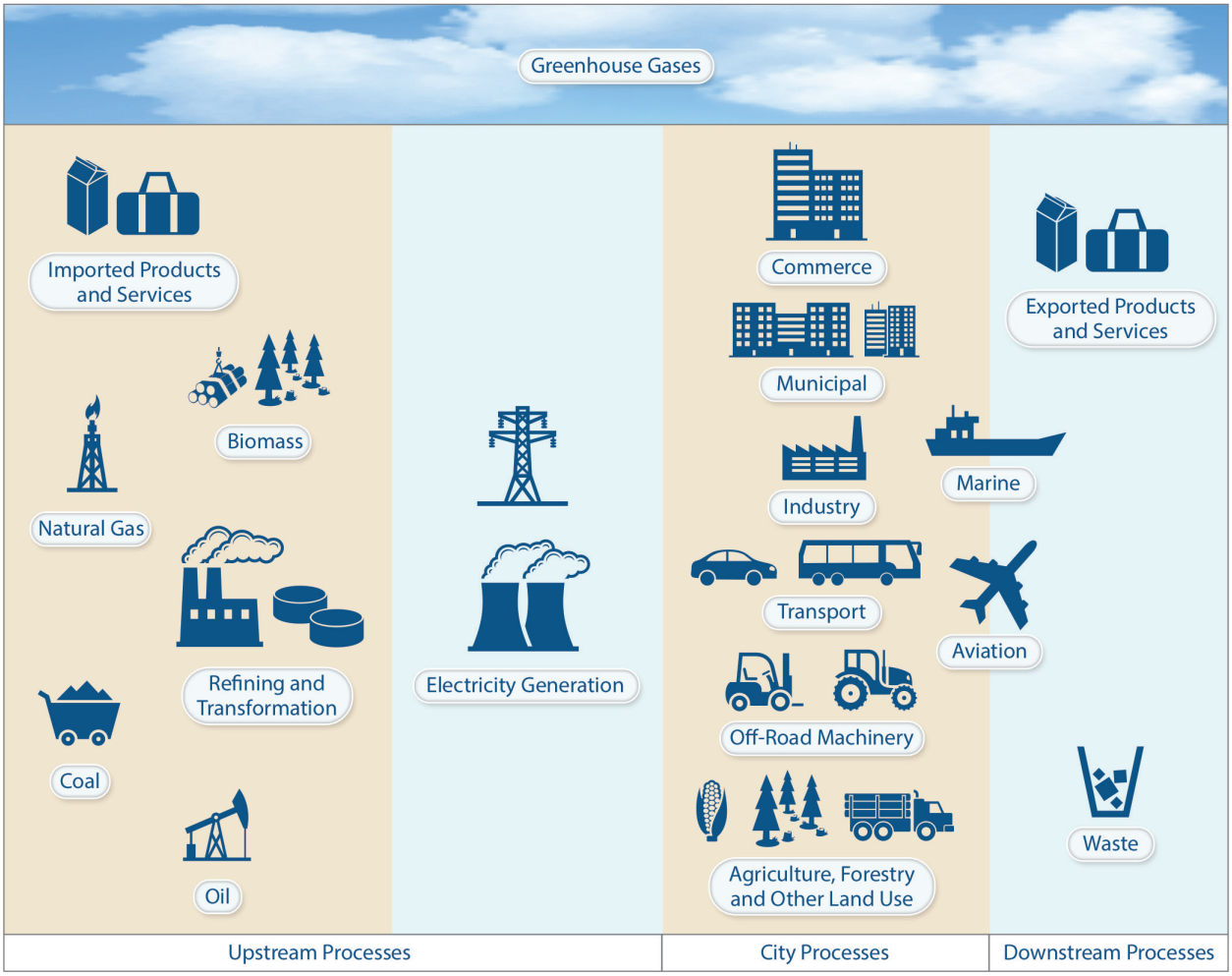

Figure 4.3. Relationships Between Carbon Inventory Approaches. Interactions are depicted between in-boundary or production-based urban carbon inventories and those that incorporate embedded or embodied carbon emissions. [Figure source: Adapted from Wright et al., 2011, used with permission.

In practice, urban carbon flux studies have used hybrids of the two frameworks, and the mixture reflects academic disciplinary interest, practical policy needs, and differing notions of responsibility or environmental justice (Blackhurst et al., 2011; Lin et al., 2015). There have been important attempts at standardizing urban carbon flux accounting frameworks via protocols or Intergovernmental Panel on Climate Change (IPCC)–approved methods (Carney and Shackley 2009; Ewing-Thiel and Manarolla 2011; Fong et al., 2014; WRI/WBCSD 2004). However, comparing urban carbon fluxes remains challenging without careful consideration of the accounting framework, city boundaries, and flux categories (Bader and Bleischwitz 2009; Hsu et al., 2016; Kennedy et al., 2009; Lamb et al., 2016; Parshall et al., 2010).

Distinct from the accounting framework used to conceptualize an urban carbon budget, the methods used to quantify urban carbon fluxes can be classified into two measurement approaches. "Top-down" approaches infer fluxes by using atmospheric measurements of CO_2 and CH_4 (and associated tracers)

and either measured or simulated atmospheric transport (Cambaliza et al., 2014; Lamb et al., 2016; Lauvaux et al., 2013, 2016; McKain et al., 2015; Miles et al., 2017; Turnbull et al., 2015; Wong et al., 2015). (See Ch. 8: Observations of Atmospheric Carbon Dioxide and Methane, p. 337, for more information on top-down approaches.) Multiple carbon sampling strategies have been used, including *in situ* stationary sampling from the ground (Djuricin et al., 2010; Miles et al., 2017; Turnbull et al., 2015), mobile ground-based sampling, aircraft measurements (Cambaliza et al., 2014, 2015), and remote sensing (Kort et al., 2012; Wong et al., 2015; Wunch et al., 2009). In addition, eddy covariance measurements have been employed on towers, buildings, and aircraft (Christen 2014; Crawford and Christen 2014; Grimmond et al., 2002; Menzer et al., 2015; Velasco and Roth 2010; Velasco et al., 2005). Recent aircraft and satellite remote-sensing studies have demonstrated the ability to map and estimate regional anthropogenic CO_2 (Hakkarainen et al., 2016) and facility-scale sources of CH_4 fluxes within cities and other complex areas (Frankenberg et al., 2016; Thompson et al., 2016).

"Bottom-up" approaches, by contrast, include a mixture of direct flux measurement, indirect estimation, and modeling. For example, a common estimation method uses a combination of economic activity data (e.g., population, number of vehicles, and building floor area) and associated emissions factors (e.g., amount of CO_2 emitted per activity), socioeconomic regression modeling, or scaling from aggregate fuel consumption (Gurney et al., 2012; Jones and Kammen 2014; Pincetl et al., 2014; Porse et al., 2016; Ramaswami and Chavez 2013). Direct end-of-pipe flux monitoring often is used for large facility-scale emitters such as power plants (Gurney et al., 2016). Indirect fluxes can be estimated through either direct atmospheric measurement (and apportioned to the domain of interest) or modeled through process-based (Clark and Chester 2017) or economic input-output (Ramaswami et al., 2008) models.

A key advance in quantifying urban carbon flux over the past decade has been the emergence of space and time bottom-up flux estimation to subcity scales (Brondfield et al., 2012; Gately et al., 2013; Gurney et al., 2009, 2012; Parshall et al., 2010; Patarasuk et al., 2016; Pincetl et al., 2014; Shu and Lam 2011; VandeWeghe and Kennedy 2007; Zhou and Gurney 2011). These approaches enable the interpretation of top-down approaches in addition to informing policy at the local scale for many cities globally (Duren and Miller 2012; Gurney et al., 2015). Despite recent attempts to integrate and reconcile various approaches to estimating urban carbon fluxes (Davis et al., 2017; Gurney et al., 2017; Lamb et al., 2016; Lauvaux et al., 2016; McKain et al., 2015), much research clearly remains to be done.

Table 4.1, p. 196, provides a sample of published research on urban carbon fluxes in North American cities, including key information about the studies, such as the accounting framework, flux measurement and estimation techniques, and references.

4.2.2 Human Activity and the Built Environment

The dominant source of carbon flux to the atmosphere from cities is associated with human activities and behaviors within the built landscape—energy use in buildings, fuel consumed in transportation (e.g., cars, airplanes, and rail), energy for manufacturing in factories, production of electricity, and energy used to build and rebuild urban infrastructure. (See Ch. 3: Energy Systems, p. 110, for more information on energy system carbon emissions and Ch. 6: Social Science Perspectives on Carbon, p. 264, for an analysis of the social and institutional practices and behaviors shaping carbon fluxes.) In addition to the combustion of fossil fuels (within and outside the urban domain), human activity within the built environment generates fluxes from 1) waste streams associated with the decomposition of materials containing carbon, 2) infrastructure leaking natural gas (composed primarily of CH_4), and 3) industrial processes that emit carbon without fuel combustion. Urban carbon fluxes associated with human activity and the built landscape often

Table 4.1. Scientifically Based Urban Carbon Estimation Studies in North American Cities

Domain	Framework, Scope, Boundary[a]	Estimation Technique[b]	Sectors Estimated[c]	References	Notes[d]
Indianapolis, IN	In-boundary	Direct flux, activity-EF, and fuel statistics; airborne eddy flux measurement; isotopic atmospheric measurement; atmospheric inversion	All FF	Cambaliza et al. (2014); Gurney et al. (2012, 2017); Lauvaux et al. (2016); Turnbull et al. (2015)	Much of the work is space and time explicit; atmospheric monitoring includes $^{14}CO_2$, CO, and CH_4
Toronto, Canada	Life cycle (scopes 1, 2)	Activity-EF	Residential	Kennedy et al. (2009); VandeWeghe and Kennedy (2007)	Annual and census tract
Los Angeles, CA	In-boundary; embedded in buildings	Atmospheric measurement; activity-EF	All FF; on-road transportation; buildings	Feng et al. (2016); Kort et al. (2012); Newman et al. (2016); Pincetl et al. (2014); Porse et al. (2016); Reyna and Chester (2015); Wong et al. (2016); Wunch et al. (2009)	Some work is space and time explicit; atmospheric monitoring includes $^{14}CO_2$, CO, and CH_4
Salt Lake City, UT	In-boundary; consumption	Atmospheric measurement; direct flux, activity-EF, and fuel statistics; forest growth modeling and eddy flux measurement	All FF; biosphere	Kennedy et al. (2009); McKain et al. (2012); Pataki et al. (2006, 2009); Patarasuk et al. (2016)	Some work is space and time explicit
Baltimore, MD	In-boundary	Eddy flux measurement	All FF; biosphere	Crawford et al. (2011)	
Denver, Boulder, Fort Collins, and Arvada, CO; Portland, OR; Seattle, WA; Minneapolis, MN; Austin, TX	Hybrid life cycle (scopes 1, 2, 3)	Activity-EF	All FF	Hillman and Ramaswami (2010)	Addition of scope 3 emissions increased total footprint by 47%

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Table 4.1. Scientifically Based Urban Carbon Estimation Studies in North American Cities

Domain	Framework, Scope, Boundary[a]	Estimation Technique[b]	Sectors Estimated[c]	References	Notes[d]
New York City, NY; Denver; Los Angeles; Toronto; Chicago, IL	Scopes 1, 2, 3	Activity-EF, fuel statistics, and downscaling	Excludes some scope 3 emissions	Kennedy et al. (2009, 2010, 2014)	
Boston, MA; Seattle; New York City; Toronto	Scopes 1, 2 (some scope 3 included); scope 1 in lowland area	Activity-EF, fuel statistics and downscaling; flux chambers and remote sensing	Excludes some sectors; biosphere carbon stock change	Hutyra et al. (2011); Kennedy et al. (2012)	
Boston	In-boundary	Activity-EF; atmospheric monitoring; atmospheric monitoring and inversion	Onroad; pipeline leak; biosphere respiration	Brondfield et al. (2012); Decina et al. (2016); McKain et al. (2015); Phillips et al. (2013)	Some work is space and time explicit; includes some CH_4
Washington, D.C.; New York City; Toronto	Scope 1	Activity-EF and fuel statistics	All greenhouse gases	Dodman (2009)	Mixture of methods from multiple sources
Chicago				Grimmond et al. (2002)	
Mexico City, Mexico	In-boundary	Eddy flux measurement; activity-EF	All FF, biosphere; onroad	Chavez-Baeza and Sheinbaum-Pardo (2014); Velasco and Roth (2010); Velasco et al. (2005, 2009)	Footprint of single monitoring location; whole-city inventory
Halifax, Canada	Scopes 1, 2	Activity-EF	Buildings, transportation	Wilson et al. (2013)	Spatially explicit
Pittsburgh, PA	Scopes 1, 2	Activity-EF, fuel statistics, and downscaling	Residential, commercial, industrial, and transportation	Hoesly et al. (2012)	
Phoenix, AZ	In-boundary	Activity-EF and soil chamber	Onroad, electricity production, airport and aircraft	Koerner and Klopatek (2002)	
Vancouver, Canada	In-boundary	Eddy flux measurement	All FF, biosphere	Crawford and Christen (2014)	

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Table 4.1. Scientifically Based Urban Carbon Estimation Studies in North American Cities

Domain	Framework, Scope, Boundary[a]	Estimation Technique[b]	Sectors Estimated[c]	References	Notes[d]
Vancouver, Edmonton, Winnipeg, Toronto, Montreal, and Halifax, Canada	Scopes 1, 2	Activity-EF	Residential building stock	Mohareb and Mohareb (2014)	
20 U.S. cities	In-boundary; consumption; hybrid	Activity-EF	All energy related	Ramaswami and Chavez (2013)	

Notes

a) In-boundary refers to fluxes exchanged within a geographic boundary of a city (equivalent to scope 1); scope 2 refers to fluxes from power production facilities allocated to the electricity consumption within the boundary of a city; scope 3 refers to fluxes from the production of goods and services consumed within the boundary of a city.

b) Estimation Technique refers to the measurement or modeling approach taken to estimate or report emissions. "Activity-EF" refers to the combination of activity data (i.e., proxies of fuel consumption) and emissions factors to estimate fluxes. "Fuel statistics" refers to methods that use estimated fuel consumption and carbon content to estimate fluxes. "Downscaling" refers to the use of estimates at larger scales downscaled to the urban scale via spatial proxies or scaling factors. "Direct flux" refers to *in situ* flux measurement distinct from eddy flux approaches, such as measurement of stack flue gases.

c) Sectors Estimated refers to the categories of emissions included in the study. They can be broadly referred to as *residential*, *commercial*, *industrial*, *transportation* (includes onroad, nonroad, airport and aircraft, waterborne, and rail), *electricity production*, and *biosphere* (includes photosynthesis and respiration). "All FF" refers to all emissions related to fossil fuel combustion (all sectors).

d) $^{14}CO_2$, radioisotopic carbon dioxide; CO, carbon monoxide; CH_4, methane.

are categorized into economic sectors such as "residential," "commercial," "industrial," and "transportation," but the descriptions vary. Similarly, the distribution of fluxes among these sector divisions varies across urban areas, depending on the many intersecting drivers of carbon fluxes including history, geography, climate, technology, energy supply, urban form, and socioeconomics.

Among these economic sectors, activities within buildings and vehicle transportation are often the largest emitters and thus have garnered the greatest amount of study. For example, depending on the urban definition adopted, recent research found that up to 77% of onroad gasoline and diesel consumption occurs in urban areas within the United States and that urban areas accounted for 80% of the onroad emissions growth since 1980 (Gately et al., 2015; Parshall et al., 2010). In Mexico City, onroad vehicles account for 44% of metropolitan emissions of greenhouse gases (GHGs) such as CO_2, CH_4, and nitrous oxide (N_2O; Chavez-Baeza and Sheinbaum-Pardo 2014), while all of the country's transportation accounts for 31% of total emissions (INECC 2012).[1] Similarly, between 37% and 86% (varying with the definition of "urban") of direct fuel consumption in buildings and industry occurs in urban areas (Parshall et al., 2010).

While urban CO_2 emissions are dominated by fossil fuel combustion (see Figure 4.4, p. 199), a large portion of urban CH_4 emissions arise from leaking natural gas infrastructure serving cities (Alvarez et al., 2012; Cambaliza et al., 2015; Jackson et al., 2014; Lamb et al., 2016; McKain et al., 2015; Phillips et al., 2013; Wennberg et al.,

[1] Also see unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/9492.php.

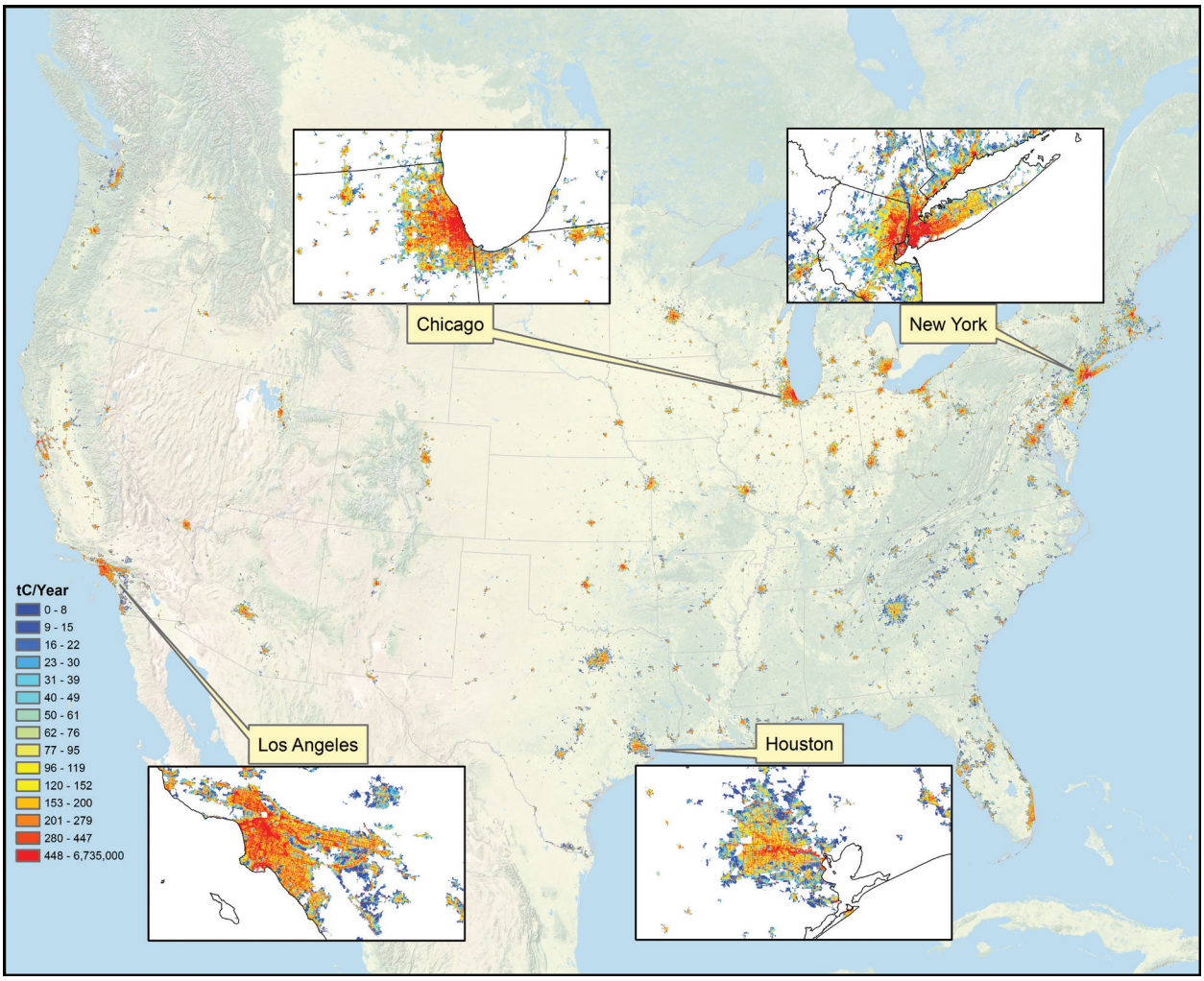

Figure 4.4. U.S. Fossil Fuel Carbon Emissions, Highlighting Four Urban Areas. [Data source: Gurney et al., 2009; units in log 10 tons of carbon (t C) per year.]

2012). (See Ch. 3: Energy Systems, p. 110, for details of leaked CH_4 emissions at the regional scale.) A study of CH_4 emissions from 13 urban distribution systems showed that emissions were roughly a factor of two smaller than U.S. Environmental Protection Agency (EPA) estimates, suggesting possible improvements in leak detection and maintenance work. However, the different methodologies between the two approaches would make assessing changes in leakage rates difficult (Lamb et al., 2015). At the same time, CH_4 emissions downstream from natural gas consumption meters on homes, buildings, and industrial facilities seem to be much higher than expected. A study in the San Francisco region suggests that emissions from the natural gas system can be equivalent to 0.3% to 0.5% of the region's natural gas consumption (Jeong et al., 2017). A similar study for the Los Angeles region estimates emissions at about 1.6% of consumption (Wunch et al., 2016). Los Angeles emissions may be higher because this region produces crude oil and natural gas. Aircraft mass balance and tower-based atmospheric inversions in Indianapolis differed by a factor of two and also exceeded the emissions estimated from a bottom-up inventory (Lamb et al., 2016).

This difference suggested that the aircraft estimate and the inventory did not account for widespread distribution of relatively small diffuse sources. These comparisons are complicated by the fact that they do not overlap in time and that emissions may be quite episodic and vary temporally. Long-term trend studies with sufficient precision to detect changes over time do not yet exist in the literature.

Methane also is produced by municipal waste facilities. In Toronto, these facilities account for as much as 10% of urban emissions (City of Toronto 2013); in Indianapolis, about 35% of emissions are attributed to one landfill (Cambaliza et al., 2015; Lamb et al., 2016).

4.2.3 Land and Ecosystems

Urban development directly and indirectly alters above- and belowground vegetation carbon pools and fluxes through land clearing, removal of vegetation, and disruption of soils (Raciti et al., 2012). Estimates of urban vegetation carbon densities vary substantially among cities or states and are based on extrapolation of limited, nonrandom sampling. Using extensive remote sensors and field observations, case studies in both Maryland and Massachusetts found that developed areas hold about 25% of the biomass per unit area of nearby forests (Huang et al., 2015; Raciti et al., 2014). Trees in urban areas in the United States and Canada store an estimated 643 teragrams of carbon (Tg C) and 34 Tg C, respectively (Nowak et al., 2013). In contrast, studies in xeric ecosystems show relative enhancement in urban biomass densities that result from landscaping preferences and addition of non-native vegetation (McHale et al., 2017).

Growing conditions for vegetation in urban areas typically differ from nonurban ecosystems, potentially accelerating the cycling of carbon and nutrients (Briber et al., 2015; Reinmann and Hutyra 2017; Zhao et al., 2016). For example, urban areas experience elevated ambient air temperatures (i.e., the "urban heat island" [UHI] effect; Oke 1982). These elevated temperatures cause seasonally dependent changes in carbon fluxes from urban vegetation and soils (Decina et al., 2016; Pataki et al., 2006; Zhang et al., 2004; Zhao et al., 2016), altering the length of the urban growing season (Melaas et al., 2016; Zhang et al., 2006). Urban respiration and growth patterns also may differ due to human additions of water and fertilizers, removal or addition of labile carbon sources (e.g., leaf litter and mulch), and planting preferences (Templer et al., 2015). Urban vegetation also can influence local climate and energy use (Abdollahi et al., 2000; Gill et al., 2007; Lal and Augustin 2012; Nowak and Greenfield 2010; Wilby and Perry 2006). For example, urban trees may affect building energy consumption and associated carbon emissions directly through shading of building surfaces and altered use of cooling equipment (Raji et al., 2015) and indirectly through local reductions in air temperature (Nowak 1993; Sailor 1998). These effects require accounting for water and energy penalties associated with irrigation of managed urban vegetation (Litvak et al., 2017). In addition, fertilization of urban landscapes and management practices such as lawn mowing can carry a high energy cost that must be assessed when determining the net effect of urban vegetation on the carbon cycle (McPherson et al., 2005; Townsend-Small and Czimczik 2010).

4.3 Societal Drivers

Investigations across a variety of research disciplines (e.g., urban economics, urban planning, urban geography, and urban physics) have tried to discern the driving factors of per capita urban carbon fluxes. International comparisons have demonstrated that economic factors such as available income and energy price levels play crucial roles, but so do urban density profiles, building age and construction, climate, and technology (Creutzig et al., 2015a).

4.3.1 Consumption

Manufacturing of goods such as clothing emits carbon if energy consumption is satisfied by fossil fuels, but consumption of goods and services, production systems, and supply chains are the fundamental drivers of emissions. As mentioned in Section 4.2.1, p. 193, accounting frameworks that

reflect a consumption perspective will allocate to the importing consumer the carbon fluxes associated with the production of goods and services. In particular, urban populations in wealthier nations that are nominally decarbonizing or stabilizing their carbon emissions often have total emissions that are increasing once traded carbon is considered in this way (Baiocchi and Minx 2010; Peters et al., 2011). Movement of goods among nations often is a result of trade policy, labor, and land costs that drive production location choices (Hertwich and Peters 2009). In U.K. cities, for example, a large carbon footprint is embedded in trade with large import partners such as China (Baiocchi and Minx 2010; Minx et al., 2013). Trade agreements, such as the North American Free Trade Agreement, have shifted automobile production and clothing manufacturing, along with their associated carbon emissions, from the United States to Canada and Mexico (Shui and Harriss 2005).

4.3.2 Economics—Wealth and Energy Prices

Economic development and urbanization reinforce each other through co-location of activities and investments (Fujita et al., 1999). In a global typology of cities, per capita gross domestic product (GDP) is identified as the most relevant sorting variable; transportation fuel prices also are relevant, distinguishing emissions among richer cities (Creutzig et al., 2015a). Urban development theories suggest that factors such as the clustering of investment and production, land development and transportation policies, and fuel prices shape urban form over the long run. For instance, incentives for dense urbanization exist when fuel prices are high and for sprawled suburbanization when prices are low, though legacy land uses—initiated during low fuel prices—continue to drive private automobile transportation use (Creutzig 2014; Fujita 1989). More recent urbanization patterns in mature cities have trended toward rehabitation or gentrification of urban cores. However, more time is needed to know the long-term impact of these patterns and whether they represent a shift toward lower GHG emissions due to less reliance on automobiles (Florida 2010). Cities also create new public transportation systems to reduce automobile dependence, but carbon fluxes from infrastructure creation remain significant in the short term (Chester et al., 2013). In an international comparison, the United States belongs to a grouping of countries with high incomes but low fuel prices. A nationwide study estimating U.S. household flux at the zip code level found that the number of vehicles per household and annual household income were the most relevant variables explaining estimated household carbon emissions (Jones and Kammen 2014). This finding illustrates the difficulties of meeting multiple policy objectives in most North American cities; when priority is given to development and urbanization, there are implications for the carbon cycle (Romero-Lankao et al., 2015, 2017).

4.3.3 Behavior—Lifestyles and Norms

Urban mobility in North America is dominated by personal automobile use, shaping and reconfiguring daily urban life (Sheller and Urry 2000). Lifestyles and norms clearly play a powerful role in explaining everyday decisions about urban mobility and energy use, but their importance as drivers for carbon emissions generally has not been studied quantitatively (Axsen and Kurani 2012; Mattauch et al., 2016; Wilson and Dowlatabadi 2007). In the United Kingdom, lifestyle changes could contribute as much to climate mitigation in the transport sector as technological changes (Anable et al., 2012). A typology of residential carbon emissions reveals that infrastructure patterns are mirrored in lifestyle classes. For example, low-emitting households in the dense urban cores of London and some U.S. cities typically are either "young professionals" or "multicultural inner city" communities of young people seeking inner-city living with downsizing or elimination of personal automobiles. Households in peri-urban London having higher emissions mostly identify as "affluent urban commuters" living in relatively inefficient houses (Baiocchi et al., 2015). However, whether these patterns are indicative of a long-term shift or merely a short-term adjustment is unclear. Another example from the Los Angeles Energy Atlas finds that wealthy neighborhoods have

higher per capita energy consumption than low-income residents who have higher consumption per unit area (Porse et al., 2016). In Salt Lake City, Utah, increments of wealth among high-income residents were found to lead to greater residential CO_2 emissions than those of low-income residents (Patarasuk et al., 2016). A systematic investigation of lifestyles, especially in interaction with urban infrastructures, has been identified as a major priority for further research (Creutzig et al., 2016). Social norms and behavior patterns in terms of energy use and consumption also exhibit carbon "lock-in," whereby norms act in isolation and in concert with institutional and technological constraints to add inertia to existing patterns of consumption and carbon emissions (see further details in Section 4.3.5, this page).

4.3.4 Urban Form and Density

Research has identified urban form and the density of cities as key drivers of urban carbon emissions (Baiocchi et al., 2015; Creutzig et al., 2015a; Karathodorou et al., 2010; Mindali et al., 2004; Newman and Kenworthy 1989, 1999). In theory, dense settlement affords energy efficiencies by encouraging multidwelling living, reduced travel distances, public transit use, and walking and cycling (Boyko and Cooper 2011; Oleson et al., 2008). In the United States, analysis has shown declines in per capita carbon emissions with increasing population density at densities greater than 1,158 persons per km^2 (Jones and Kammen 2014). At lower densities, typical of suburban areas, carbon emissions rise with increases in density (Glaeser and Kahn 2010; Jones and Kammen 2014). These results are supported by recent research on transportation energy consumption (Liddle 2014), electricity consumption in buildings (Lariviere and Lafrance 1999), and overall urban carbon emissions (Marcotullio et al., 2013). A recent study found that the high correlation between per capita electricity use and urbanized area per person can be explained by the higher per capita building floor area in less-dense cities (Kennedy et al., 2015).

Urban form and density are determined by local plans, existing infrastructure, land costs, and public attitudes (Ewing and Rong 2008). These factors often are determined by local actions and constrained by national, state, or other regulations, such as the Federal Emergency Management Agency's 100-Year Flood Maps, insurance policies, and perceived costs of existing infrastructure and land. Change in land-use patterns, as well as services such as public transportation, require long-term commitment, public support, and funding. Once a pattern has been set, it tends toward obduracy, making change difficult (Unruh 2000). Zoning codes that segregate land uses contribute to urban sprawl and a car-dependent road infrastructure that, in turn, influences carbon emissions (Fischel 2015; Hamin and Gurran 2009). These rules vary across states, provinces, and cities because of different relationships of autonomy between cities and other governmental scales. Policy drivers may be generated at the different scales, including national (e.g., transportation infrastructure investments), state, provincial (e.g., requirements for cities to create general plans or set building codes), or city (e.g., specific zoning codes; Knaap et al., 2015). These rules, codes, and standards establish frameworks for cities, including facilitating sprawled urban form through road subsidies or land regulation or encouraging density and efficient building through strict building codes and tax policy that discourages automobile use and ownership (Grazi and van den Bergh 2008). Stricter land-use regulation can induce sprawl development in nearby suburban and peri-urban areas, an occurrence that may increase overall carbon emissions. That is, cities with stricter land-use regulations externalize development to adjacent communities with more lenient regulations, engendering higher rates of suburbanization in the region (Glaeser and Kahn 2010). Harmonization of land-use regulation or higher fuel taxes can reduce the likelihood of this outcome.

4.3.5 Technology

Technological attributes, such as power generation (see Ch. 3: Energy Systems, p. 110), urban design, and waste processing, partly determine city profiles for carbon emissions (Kennedy et al., 2009). Availability of low-carbon technologies reduces urban per

capita carbon emissions. For example, cities with carbon intensity of electricity below approximately 600 metric tons (t) CO_2 equivalent[2] (CO_2e) per gigawatt hour (GWh), such as Los Angeles, New York City, and Toronto, can reduce life cycle carbon emissions through electrification of transportation and heating systems (Kennedy 2015; Kennedy et al., 2014). However, because of the relative permanence of large technological and infrastructural systems in urban areas, the notion of infrastructure lock-in is critical and often makes shifts to low-carbon technologies and systems costly or not feasible (Unruh 2000). Lock-in results from the high cost of the infrastructure; the expended energy in the infrastructure; and the social systems of regulation, codes, and conventions that reinforce existing systems (Pincetl et al., 2016; Reyna and Chester 2015; Seto et al., 2016). However, technology is influenced by institutions, individual behavior, and policy actions (Chester et al., 2014), and technology has replacement or turnover cost implications with fossil fuel–burning infrastructure having lifetimes of up to 50 years (Erickson et al., 2015; see Figure 4.5, p. 204). The issue of carbon lock-in is another example of the interactions, constraints, and opportunities that involve multiple scales of governance beyond urban domains.

In 16 U.S. states and Washington, D.C., regulatory changes, such as Incentives for Renewables and Efficiency, are both facilitating and requiring decarbonization of energy (www.nrel.gov/tech_deployment/state_local_governments/basics_portfolio_standards.html). U.S. public utilities commissions (PUCs) regulate the large investor-owned utilities, and PUCs of states such as New York and California are creating new regulatory frameworks for increased renewable energy generation, purchase, and storage to decrease reliance on fossil fuel–generated energy. In 2015, California established a 50% renewable portfolio standard for the electricity system that is to be accomplished by 2030 (Senate Bill 350). The state also adopted a new legal mandate in September 2016 requiring statewide reductions of GHG emissions by 40% from 1990 levels by 2030 (Senate Bill 32).

4.3.6 Climate

Local climate is also a modifier of urban carbon emissions in conjunction with socioeconomic and urbanization characteristics (Baiocchi et al., 2015; Creutzig et al., 2015a; Glaeser and Kahn 2010; Kennedy et al., 2015). Global climate change typically modifies local energy use by reducing heating and increasing air conditioning demands (Huang and Gurney 2016). Local climate also can be partly influenced by human activity via the UHI effect (Boehme et al., 2015; Georgescu et al., 2014; Oke 1982), which, in turn, drives changes in energy consumption and carbon emissions (Lin et al., 2015; Wang et al., 2010).

4.4 Trends and Feedbacks

A quantitative understanding of contemporary urban carbon trends continues to face limitations related to data availability across the North American domain. Some understanding can be gleaned from statistics on urban growth in general, along with several case studies of urban carbon fluxes over particular time spans or locations. For example, Mexico's annual urban population grew at a rate of 1.9% between 1995 and 2015, while both Canada and the United States had urban growth rates of 1.2% (UN DESA 2015). Future projections at the global level and for North America suggest increases in urban land use. For example, there is a greater than 75% probability that global urban land will increase from 652,825 km^2 in 2000 to 1,863,300 km^2 in 2030 (Seto et al., 2012). Other studies have projected a near tripling in the percentage of land devoted to urban cover by midcentury (Nowak and Walton 2005).

The future trajectory of urban carbon fluxes is unambiguously tied to increases in aggregate urban energy demand and the proportion met by fossil fuels (Hoornweg et al., 2011; Jones and Kammen 2014; Marcotullio et al., 2013). Theoretically, these

[2] Carbon dioxide equivalent (CO_2e): Amount of CO_2 that would produce the same effect on the radiative balance of Earth's climate system as another greenhouse gas, such as methane (CH_4) or nitrous oxide (N_2O), on a 100-year timescale. For comparison to units of carbon, each kg CO_2e is equivalent to 0.273 kg C (0.273 = 1/3.67). See Preface for details.

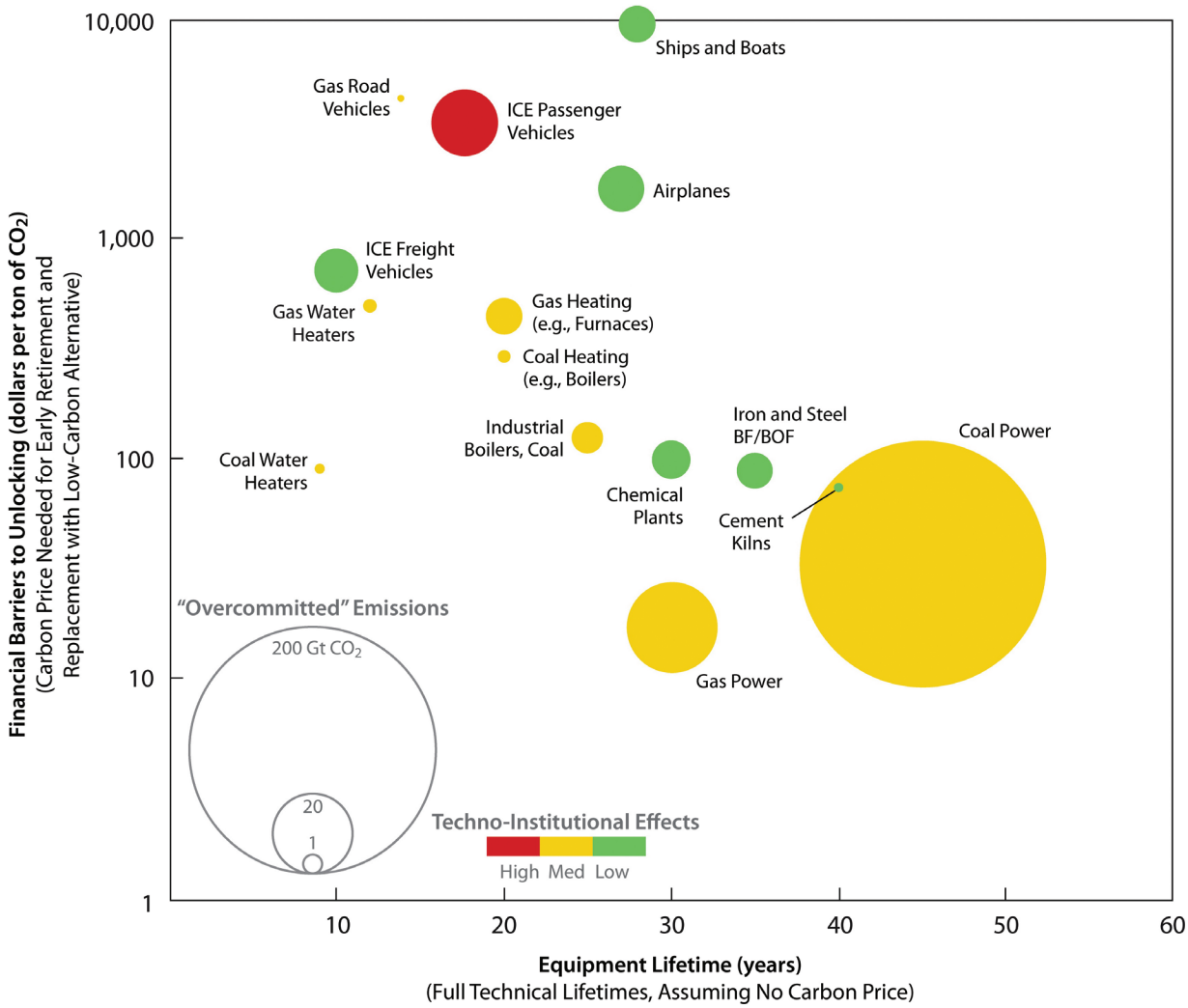

Figure 4.5. Assessments of Lock-In Related to Different Types of Infrastructure Emitting Carbon Dioxide (CO_2). Different fossil fuel–burning infrastructures are plotted according to their historical lifetime (x-axis) and the carbon price (in dollars per ton of CO_2) required to equalize the marginal cost of existing infrastructure (mainly fuel) with the total levelized cost (i.e., including capital and operating expenses) of a low-carbon replacement (y-axis). Circle sizes reflect the cumulative future emissions of each type of infrastructure that are in excess of what that infrastructure can emit under a 2°C climate scenario. Colors are qualitative indicators of the techno-institutional resistance of that type of infrastructure to unlocking (e.g., stocks of very specific intellectual capital, established subsidies, entrenched social norms, large supporting infrastructures, and political influence). Key: ICE, internal combustion engine; BF, blast furnace; BOF, basic oxygen furnace; Gt, gigaton. [Figure source: Redrawn from Seto et al., 2016 (originally adapted from Erickson et al., 2015), used with permission.]

increases are the cumulative result of concentrated population and economic activity, which today are predicated on the more energy intensive processes in agriculture, transportation, buildings, industry, and waste management (Liddle 2014). However, despite consensus about the positive correlation between population and energy demand or carbon emissions, there is debate about the magnitude of the effect and the implications of future urbanization. The effect of population size on carbon

emissions or energy demand may be contingent on other factors, including, for example, a city's starting population size (Bettencourt et al., 2007). Some evidence for this scaling relationship suggests that urban areas with larger population sizes have proportionally smaller energy infrastructures than smaller cities (Bettencourt et al., 2007; Fragkias et al., 2013). Other evidence suggests that carbon emissions may increase at a rate greater than population growth rates, so that larger cities exhibit proportionally higher energy demand as they grow than do smaller cities (Marcotullio et al., 2013). Theoretically, such an outcome is possibly due to diminishing returns, threshold effects, negative synergisms, and the disproportionate escalation of cost for maintaining environmental quality with population growth (Ehrlich and Holdren 1971). Finally, the difficulty occurs with predicting not only trends in policymaking, but also the impact of policy change on energy sources (Tuckett et al., 2015). For instance, in some U.S. states, policy is shifting some of the energy generation toward renewables (Lutsey and Sperling 2008). However, cost drivers for energy sources evolve over time and influence the choice of energy supply (Gan et al., 2007).

The generation of waste heat, coincident with carbon emissions from the combustion of fossil fuels, has the potential to initiate feedbacks with the urban carbon cycle through the UHI effect—a phenomenon whereby urban areas are warmer than their unbuilt surroundings (Boehme et al., 2015; Oke 1982). Averaged at the city scale, the magnitude of this waste heat can be up to 100 watts per m^2 (Sailor et al., 2015), potentially increasing urban warming by 2 to 3°C in winter and 0.5 to 2°C in summer (Fan and Sailor 2005). As urban areas warm due to both large-scale changes in climate and localized UHI, the energy consumed for space cooling in summer increases while the energy used for heating in winter decreases, "spilling over" into other seasons (Li et al., 2015; Wang et al., 2010). For example, recent research found that summer electricity demand may increase up to 50% in some U.S. states at the end of this century due to increased cooling needs under climate change alone (Huang and Gurney 2016). In fact, a recent modeling study by Georgescu et al. (2014) found that for U.S. cities, the effects of urban expansion on urban air temperatures by 2100 will be on the same order of magnitude as GHG-induced climate change. The UHI effect, in addition to changes in heatwave event frequency and magnitude, would further exacerbate this feedback (Li and Bou-Zeid 2013).

4.5 Global, North American, and Regional Context

4.5.1 Global Urban Carbon

Of the nearly 1,000 urban agglomerations with more than 500,000 people across the world, three-quarters are in developing countries (UN DESA 2015). The share of energy-related urban CO_2 emissions worldwide is 71%, somewhat less than the share in North America (IEA 2008). Given the greater levels of current urbanization in North America and recent trends across the world, most future urban growth and associated urban carbon emissions likely will be dominated by low- and middle-income countries. In smaller urban areas within the United States and Europe, de-urbanization is occurring (Martinez-Fernandez et al., 2012), and its implications for carbon emissions are still poorly understood.

Within the global context, North America (particularly Canada and the United States) has smaller urban population densities but greater per capita built-up area (Seto et al., 2014). Due to extensive urbanization levels and fossil fuel consumption associated with transportation and urban infrastructure, North America has the largest percent of total carbon emissions emanating from urban areas (Marcotullio et al., 2013).

4.5.2 United States, Canada, and Mexico—Urban Carbon in Context

Cities in the United States and Canada generally have recorded amongst the highest per capita carbon emissions when compared to global cities (Dodman 2009; Hoornweg et al., 2011; Kennedy et al., 2009; Sovacool and Brown 2010). In cities for which there

are repeat carbon inventories (e.g., Boston, New York City, Toronto, and Seattle, from 2004 to 2009), per capita emissions are declining at the same rate as national inventories (Kennedy et al., 2012). But when indirect emissions are included in city inventories, urban per capita emissions are about the same as national per capita emissions (Ramaswami et al., 2008). This measurement further highlights the importance of understanding indirect carbon fluxes and the increase in the export of emissions outside the North American urban domain. Core aspects of per capita energy and material consumption have been found to be inversely correlated to urban population density (Kennedy et al., 2015).

4.6 Carbon Management Decisions

Since the mid-1990s, cities around the world have increasingly engaged in carbon management efforts, reflecting a growing recognition that cities are both locations where emissions-producing activities occur and political jurisdictions with authority over some of those activities (Castan Broto and Bulkeley 2013). The number of cities that have committed to some form of carbon reduction has increased exponentially, from fewer than 50 in the early 1990s, several hundred by the early 2000s (Bulkeley and Betsill 2003), and several thousand a decade later (Krause 2011; Pitt 2010). North American cities have played a particularly important leadership role, emerging as key sites for experimentation and innovation with different types of policies, technologies, and programs (Burch 2010; Castan Broto and Bulkeley 2013; Hoffmann 2011; Hughes and Romero-Lankao 2014, 2015).

4.6.1 Importance of Governance and Multilevel Networks

Key factors in the ability of city governments to manage carbon emissions are the mandates and competencies of municipal governments, financial resources, presence of political champions, multilevel networks, an open political opportunity structure, and the ability to capitalize on co-benefits valued by local residents (Betsill and Bulkeley 2007; Ryan 2015). Local authorities in North America also encounter a number of barriers, including the lack of coordination across different parts of city government, sunk investments in infrastructure, and resistance to change of the local political economy (Romero-Lankao et al., 2013, 2015; Sharp et al., 2010; Tang et al., 2010; Tozer 2013). A recent study found that U.S. city membership in the International Council for Local Environmental Initiatives (ICLEI) declined 22% between 2010 and 2012 and that large numbers of cities had abandoned their climate policy efforts altogether (Krause 2015).

Local carbon mitigation efforts also are limited by infrastructure lock-in and "path dependencies" created from previous policy decisions and investments, which can make changing direction politically difficult and expensive (Unruh 2000). Path dependency is a function of infrastructure cost and life cycle and is influenced by the way that decisions are made (Romero-Lankao et al., 2017). For instance, the low-density urban form of North American cities such as Los Angeles has been largely the result of freeway construction programs of the California Division of Highways (Wachs 1993). These decisions have created a path-dependent use of private vehicles, associated with more energy use and more carbon emissions (Kenworthy 2006).

There is one important difference in the policy contexts of cities in the United States, Canada, and Mexico. Cities occupy different jurisdictional space and face different economic, institutional, and political contexts. Decision making in the United States is generally more decentralized than that in Canada and Mexico, potentially giving city governments more autonomy (Bulkeley and Betsill 2013). Notwithstanding these across-country differences, the challenges and opportunities cities face, such as economic development, air pollution, and transit access, vary as much within countries as between them. For example, policy aimed at mitigation of local air pollution has resulted in climate policy co-benefits in most large North American cities, including Mexico City, but results typically are not as salient for smaller cities (Romero-Lankao 2007).

While municipal governments have some control over carbon emissions, urban carbon management ultimately takes place in a multilevel governance context, whereby climate policy efforts have the potential to be spread across different levels of political jurisdiction and pursued through diverse forms of governance instruments (see Ch. 3: Energy Systems, p. 110; Ch. 6: Social Science Perspectives on Carbon, p. 264; and Ch. 18: Carbon Cycle Science in Support of Decision Making, p. 728). For example, utilities can be governed by federal, regional, and state institutions and by public, private, and nonprofit partnerships that each make decisions on policy, infrastructure, and the mix of power generation in the electricity grid (Bulkeley 2010; Pincetl et al., 2016; Schreurs 2008). Municipal priorities and outcomes are shaped not only locally, but also by international agreements; national policies, legislation, and regulation; and state- and provincial-level efforts such as the adoption of renewable portfolio standards and the initiation of emissions trading markets (Bulkeley 2010; Bulkeley and Betsill 2013; Burch 2010; Romero-Lankao et al., 2017). National and state or provincial policies shape urban management efforts by creating a permissive or restrictive institutional setting for local action (Bulkeley and Betsill 2013; Burch 2010; Homsy and Warner 2014; Romero-Lankao et al., 2013, 2015, 2017). For example, federal and state agencies (e.g., public utility commissions) independently shape a number of energy-supply characteristics through rules, regulations, and standards. In California, state-level regulations are playing a significant role in spurring local action, such as calling for Zero Net Energy residential buildings by 2020, doubling energy efficiency for the existing building stock by 2030, and meeting renewable portfolio standards. In many North American cities, there is relatively little explicit interaction or coordination among these different levels of government (Betsill and Rabe 2009; Jacoby et al., 2014).

Thousands of North American cities and towns have joined municipal networks such as the C40 Cities Climate Leadership Group and the ICLEI (Kern and Bulkeley 2009; Robinson and Gore 2011), though participation is declining, as noted. Municipal climate change networks play a role in generating norms and standards for setting targets and monitoring and measuring progress (Betsill and Bulkeley 2004). These networks also provide opportunities for information sharing and capacity building. Cities join such networks to demonstrate leadership and secure recognition. However, the impact of network membership on local implementation or broader-scale policy change has yet to be demonstrated (Gore 2010; Krause 2012).

4.6.2 Sectoral Mitigation Approaches

Three urban sectors have been identified as key for mitigating urban carbon emissions: the built environment, transportation, and energy systems (see Section 4.2.2, p. 195). Carbon emissions from energy use in buildings can contribute as much as 80% of a city's total and primarily are controlled by private building owners (Rosenzweig et al., 2010). As a result, states and local authorities in many North American cities have begun to partner with private actors—the owners of these buildings—to integrate carbon mitigation and transition to low-carbon development within broader urban agendas (Bulkeley and Betsill 2013; Bulkeley and Castán Broto 2013; Hodson and Marvin 2010; While et al., 2010). Reducing energy consumption through energy-efficient building design and construction is an ongoing effort at the state and local levels in North America (Griego et al., 2012; Koski 2010; Larsson 1999). Mexico hosts the seventh largest green building market in the world,[3] and Canada is the largest green building market outside the United States. Cities also can incentivize or require energy conservation more directly. Energy-use benchmarking policies for the private sector are being promoted for North American cities, several of which have adopted these policies including New York City, Philadelphia, San Francisco, and Seattle (Cox et al., 2013). New York City's Greener, Greater Buildings program benchmarks energy use in private buildings and mandates energy efficiency

[3] www.gbes.com/blog/mexico-is-a-leed-leader/

and conservation measures (Block and Semel 2010). Similarly, California's Senate Bill 802 may make benchmarking mandatory for commercial buildings.[4] These examples have informed the National Resources Defense Council's City Energy Project, which is helping cities introduce benchmarking and conservation efforts of their own. The actual performance of buildings also depends on correct equipment installation, occupant behavior, and attitudes toward energy conservation (Mills and Schleich 2012; Virote and Neves-Silva 2012). Additionally, local authorities in Toronto are piloting a carbon credit trading program, and many cities have placed energy use and efficiency at the center of their climate change mitigation efforts (IEA 2015; Sun et al., 2015). California's Title 24 building codes, first established in 1978, have required increasingly stringent energy conservation for buildings, including insulation, window glazing, and more. These codes are credited for much of the state's energy savings (CEC 2015), but there also is evidence for a rebound effect as buildings, though more efficient, are bigger overall (Porse et al., 2016). Finally, the energy embodied in building construction can be incorporated into green building policy (Biswas 2014; Hammond and Jones 2008; Reyna and Chester 2015). Accounting and labeling systems, for example, measure and inform consumers about the environmental impacts of a structure (Dixit et al., 2010; Monahan and Powell 2011).

Transportation mitigation options include facilitating the transition to lower-emission vehicles and expanding the availability and use of public transit (Creutzig et al., 2015b). Cities are building electric vehicle charging stations, requiring low-emission vehicles in their own fleets, and encouraging biking and walking. Transit-oriented developments are designed to reduce the carbon emissions correlated with low-density suburban sprawl (Glaeser and Kahn 2010), though high capital costs and fragmented decision making continue to pose challenges. Additional challenges include long-term tradeoffs regarding the carbon impacts of different transit and fuel-mix options that continue to be evaluated (Chester et al., 2013).

Because cities consume about 75% of power generation worldwide (Dodman 2009), a common mitigation focus for cities is energy production itself. Many cities do not have formal authority to dictate the fuel sources for their energy supply and thus must rely on action from other levels of government and the private sector (Kern and Alber 2009). Reliance and cooperation require indirect action on the part of city governments, such as facilitating or incentivizing the expansion of renewable energy sources and lobbying relevant decision-making bodies. Examples include Toronto and Halifax's use of deep lake water to cool buildings, though there are barriers to scaling up such technologies (Newman and Herbert 2009). At the same time, there is increasing understanding of the need to couple solar generation with storage. Currently, "excess solar" generated in the middle of the day is not stored, requiring other electricity generation sources for peak load times and in the evening. Often this energy is provided by natural gas "peaker" power plants that constantly are powered, emitting CO_2 (St. John 2014).

Cities often have more direct control in areas such as waste-to-energy schemes and local distributed solar generation. For example, CH_4 capture at two of Toronto's largest landfills is responsible for just over 10 million tons of GHG reductions since 2004 (City of Toronto 2007, 2015). In California, local governments have begun to create Community Choice Aggregation alternative utilities that offer customers greater proportions of renewable energy (Roberts 2015). Key to ensuring the success of these programs is maintaining the subsidies and incentives to overcome behavioral and technological challenges (Kammen and Sunter 2016).

Two additional urban carbon cycle components deserve mention when considering sectoral mitigation approaches: CH_4 leakage (referred to as "fugitive" emissions) and urban vegetation. As mentioned in Section 4.2.2, p. 195, several studies have identified CH_4 emissions from leaking

[4] www.energy.ca.gov/sb350/

natural gas infrastructure serving cities (Jackson et al., 2014; Lamb et al., 2016; McKain et al., 2015; Phillips et al., 2013). Methane emissions also can occur downstream of building meters, for example, from leaky gas pipes in buildings, stoves, hot water heaters, and other appliances (Jeong et al., 2017; Lavoie et al., 2017; Wunch et al., 2016). The quantity of CH_4 emissions from the natural gas system is not well constrained (Brandt et al., 2014; Hendrick et al., 2016; Lamb et al., 2016; McKain et al., 2015), but there are specific thresholds for CH_4 loss from natural gas, which, if exceeded, would negate the climate benefit of switching to natural gas. According to Alvarez et al. (2012),[5] realizing an immediate net climate benefit from the use of natural gas would require CH_4 emissions from the natural gas system to be lower than 0.8%, 1.4%, and 2.7% of production to justify a transition from heavy-duty diesel vehicles, gasoline cars, and coal-burning power plants, respectively.

At the municipal scale, reports indicate that biological carbon uptake within urban boundaries constitutes 0.2% to 3% of total emissions, depending on the locality (Escobedo et al., 2010; Liu and Li 2012; Tang et al., 2016; Velasco et al., 2016). However, biological carbon respiration rates are sensitive to management practices (e.g., Decina et al., 2016), and urban vegetation possibly can constitute a net source of carbon to the atmosphere. The role of urban vegetation dynamics may be much more significant in affecting emissions through indirect impacts on the urban carbon cycle, such as shading of buildings that reduces energy consumption, evaporative cooling of urban vegetation, and wind sheltering (Akbari et al., 2001; Shashua-Bar et al., 2009; Susca et al., 2011). These indirect carbon reductions—a result of urban vegetation on energy consumption rather than direct carbon emissions–reducing technologies, for example—must be weighed against the energy and water penalty of increasing vegetation cover in locales with little or no historic vegetation canopy, such as the southwestern United States (Middel et al., 2014, 2015).

4.6.3 Co-Benefits and Tradeoffs—Links to Air Quality, Health, and UHI

Studies have identified co-benefits between carbon mitigation in urban areas and improvements in human health and other urban environmental issues (Harlan and Ruddell 2011; Milner et al., 2012; Viguié and Hallegatte 2012; see Ch. 6: Social Science Perspectives on Carbon, p. 264). For example, reducing fossil fuel consumption or CH_4 emissions also decreases emissions of traditional air pollutants such as carbon monoxide (CO), sulfur oxides (SO_x), volatile organic compounds (VOC), particulates, and oxides of nitrogen (NO_x). Three of these—NO_x, VOCs, and CO—are associated with the production of ground-level ozone, which is linked to respiratory diseases such as emphysema, bronchitis, and asthma (Kim et al., 2011). Various studies have linked fine particulate exposure to significant health problems including aggravated asthma, chronic respiratory disease in children, and premature death in people with heart or lung disease (Valavanidis et al., 2013). However, carbon mitigation practices also have tradeoffs. For instance, renewable energy systems that lower carbon emissions and reduce health impacts of traditional air pollutants are not completely free from environmental and health impacts (Miller et al., 2013).

Carbon emissions often are associated with waste heat production, which plays a role in the UHI effect. Strategies that reduce fossil fuel carbon emissions may contribute to reduced waste heat and, subsequently, a decrease in both summer and winter urban air temperatures. The magnitude of urban cooling may be modest and dependent on the location and timing of reduced energy consumption (Huang et al., 2013; Ostro et al., 2011; Sarofim et al., 2016) and the fuel mix used for electricity production and building heating systems (Jacobson and Ten Hoeve 2012).

[5] These numbers were modified from the Alvarez et al. (2012) study by the Environmental Defense Fund to account for new data (see www.energy.ca.gov/2014_energypolicy/documents/2014-06-23_workshop/presentations/13_O_Connor_EDF_IEPR-Presentation.pdf).

4.7 Synthesis, Knowledge Gaps, and Outlook

Dozens of completed or underway studies on urban carbon flux are now reported in the peer-reviewed literature (see Table 4.1, p. 196). Among these are intensive efforts testing different methods and approaches to understanding flux magnitudes, trends, driving activity, emissions mitigation guidance, and reduction performance tracking. Despite these efforts, consistent and comparable data on carbon fluxes in cities are still lacking, particularly at spatial resolutions below the whole-city level (Kennedy et al., 2015). Greater integration of these studies and greater exploration of whether and how this information can be used by stakeholders are needed. This will require continued efforts in interdisciplinary integration of existing subcommunities engaged in urban carbon research. For example, the use of sometimes singular reliance on atmospheric concentration observations common in inversion studies could move toward an assimilation framework in which all available observational constraints are incorporated with their accompanying uncertainties to arrive at optimized carbon fluxes, further integrating bottom-up and top-down approaches. Equally important are 1) the integration of information on CO_2, CH_4, and relevant local air pollution and 2) the continued trend toward data with higher space and time resolutions, particularly relevant to urban stakeholders. Finally, integration across ongoing urban studies will provide more insight into which research methods and approaches are successful under differing urban morphologies and social and physical constraints (e.g., urban density, data transparency, and topography). These advances could be achieved in part by integrating existing approaches with remote sensing of urban CO_2 and other attributes relevant to the urban carbon cycle.

Urban carbon trends remain difficult to assess because of a lack of compatible and comparable data and limited historical information. Results from a number of intensive studies underway should begin to inform trend information in North America. Improvement to trend detection is critical to the assessment and prognostic capabilities important to urban stakeholders. Integration of urban trend detection with trend activity at larger scales could advance the ability of observing systems to systematically assess urban trends.

Urban carbon fluxes are dominated, directly and indirectly, by the human activities within the built environment that includes large infrastructural systems such as buildings, roads, and factories, along with their co-evolution with fossil fuel energy sources. The carbon fluxes associated with this co-evolved technological system are modulated by underlying climate and socioeconomic dynamics such as consumption, wealth, lifestyles, social norms, governance, and energy prices. A quantitative understanding of these drivers and flux outcomes remains difficult to generalize. This challenge is due to both the emergent properties of urban carbon fluxes and the idiosyncratic nature of cities and the studies performed thus far, which tend to focus on single urban domains. Particularly in Mexico, for example, little work has been accomplished outside the Mexico City metropolitan area. More research is needed that systematically explores multiple urban domains to better understand the relationships between emissions and the physical, social, and technological dynamics in cities.

The urban domain is a source of significant carbon mitigation potential evidenced by the rapid rise in individual urban-scale climate policy efforts. This mitigation, combined with the dominant role that cities play in total anthropogenic carbon emissions, implies that proposed emissions mitigation measures must be tested against documented success in urban areas. The ability of cities to manage carbon fluxes is determined by what control cities can exert over flux sources or their drivers. Cities and their carbon management efforts exist within a larger multilevel governance matrix that can both enable and hinder carbon mitigation efforts. For example, without control over energy supply systems, some cities have limited capability to mitigate emissions.

More targeted research evaluating how specific reductions in emissions are linked to specific policies would enhance the ability to design and implement effective policies in the future. There is limited evidence on the effects of urban climate policy on reducing community-wide emissions, advancing other urban policy goals, or contributing to a transition to low-carbon development. Attributing changes in urban carbon emissions to the actions of city governments also can be challenging, partly because of the complex networks of authority at play. Moreover, there has been little effort to study other effects of urban climate policy, such as cost-effectiveness, co-alignment with other goals and processes, and distributional effects on marginalized populations. Without common frameworks and comparable case studies, the extent to which local or distant political and economic factors shape these outcomes is unclear.

Given the increasing role that urban areas play in the total carbon fluxes within the three North American countries, there is a critical need to improve urban carbon flux projection capabilities in North American cities. Better information on fluxes and their drivers, combined with improved understanding of successful mitigation, would offer researchers and urban decision makers the means to bend urban flux trajectories toward low-carbon pathways. Continued work on the co-benefits and tradeoffs associated with carbon mitigation practices will further enrich carbon emissions planning to account for the important related issues of the UHI, urban air quality, and human health.

SUPPORTING EVIDENCE

KEY FINDING 1

Urban areas in North America are the primary source of anthropogenic carbon emissions, with cities responsible for a large proportion of direct emissions. These areas are also indirect sources of carbon through the emissions embedded in goods and services produced outside city boundaries for consumption by urban dwellers (*medium confidence, likely*).

Description of evidence base

Key Finding 1 is supported by empirical evidence and modeling studies aimed at quantifying and understanding urban extent, energy, carbon, and material flows (Jones and Kammen 2014; Hoornweg et al. 2011; Seto et al., 2014). Research has highlighted the importance of direct versus indirect carbon fluxes in addition to the relative importance of urban carbon flows within the national landscape (Lin et al., 2015).

Major uncertainties

Very few studies have attempted a comprehensive assessment of the urban portion of North American carbon emissions. Only two have attempted estimates for the North American domain (Marcotullio et al., 2013; Grubler et al., 2012). Both contain unquantified uncertainties acknowledged to include not only the underlying data, but also the definition of "urban" and objective methods to spatially enclose urban areas (Parshall et al., 2010). Uncertainty also exists in the exact quantification of urban versus nonurban carbon emissions because of limited data and methodological inconsistencies in defining direct and indirect carbon fluxes.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Key Finding 1 is supported by a growing number of urban carbon footprint studies in North America. Much of this work is in the United States, with some work in Canada and very few studies in Mexico. There is general agreement that urban areas constitute the majority of anthropogenic carbon emissions in North America. However, a more precise assessment remains uncertain because of a lack of comprehensive data. Recent formalization of methods now defines direct versus indirect anthropogenic carbon emissions, but these methods are applied inconsistently in studies of urban carbon emissions, challenging attempts to compare emissions among cities.

Summary sentence or paragraph that integrates the above information

For Key Finding 1, anthropogenic carbon fluxes associated with North American cities represent the majority of total anthropogenic carbon emissions from North America, though uncertainty remains on the precise share. These emissions consist of both direct and indirect emissions, the latter of which are recognized as important, but often poorly characterized, components of total urban anthropogenic carbon flux.

KEY FINDING 2

Many societal factors drive urban carbon emissions, but the urban built environment and the regulations and policies shaping urban form (e.g., land use) and technology (e.g., modes of transportation) play crucial roles. Such societal drivers can lock in dependence on fossil fuels in the absence of major technological, institutional, and behavioral change. Some fossil fuel–related infrastructure can have lifetimes of up to 50 years (*high confidence*).

Description of evidence base

Key Finding 2 involves societal factors that drive urban carbon emissions, including consumption and supply chains (Baiocchi and Minx 2010; Peters et al., 2011), wealth (Creutzig et al., 2015a), fuel prices (Creutzig 2014), lifestyle and norms (Patarasuk et al., 2016; Porse et al., 2016), urban form and density (Baiocchi et al., 2015; Creutzig et al., 2015a; Karathodorou et al., 2010; Mindali et al., 2004; Newman and Kenworthy 1989, 1999), technology (Kennedy et al., 2009, 2014, 2015), and climate (Baiocchi et al., 2015; Creutzig et al., 2015a; Glaeser and Kahn 2010; Kennedy et al., 2015). Research continues to establish the relative permanence of large technological and infrastructural systems in urban areas. For example, fossil fuel–burning infrastructures have lifetimes up to 50 years, leading to systemic dependence (i.e., "lock-in") on fossil fuel–based technology (Unruh 2000; Seto et al., 2016; Erickson et al., 2015).

Major uncertainties

Increasing numbers of studies examine relationships between urban density and 1) atmospheric emissions and 2) building energy use. Uncertainty exists relative to the ability of cities to change their infrastructure because of cost considerations and municipal regulations, as well as state and national regulations that affect city form and infrastructure. Relationships among the core elements of carbon lock-in (i.e., technological, institutional, and behavioral) are poorly understood and involve interactions among scales of governance larger than urban areas. All these aspects vary widely across cities and North American countries.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Studies are emerging that investigate these relationships, but more research is needed to understand the processes.

Summary sentence or paragraph that integrates the above information

For Key Finding 2, cities are complex systems with a mix of societal factors driving carbon emissions. Uncertainties remain regarding a complete typology of driving factors and the extent to which these factors lead to path dependencies and the ability of urban areas to alter infrastructure and technological trajectories.

KEY FINDING 3

Key challenges for urban carbon flux studies are observational design, integration, uncertainty quantification, and reconciliation of the multiple carbon flux approaches to detect trends and inform emissions mitigation efforts (*medium confidence, likely*).

Description of evidence base

Key Finding 3 is supported by recent research that begins to integrate and reconcile carbon flux information from intensive urban study sites in North America. Key supporting references include Gurney et al. (2017), Lamb et al. (2016), Lauvaux et al. (2016), and McKain et al. (2012, 2015).

Major uncertainties

The major uncertainties related to integrating and reconciling urban carbon budget studies are those intrinsic to the different methodologies used. For trend detection and mitigation guidance, major uncertainties arise from the differences in scientific goals versus policy application.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is broad agreement that integration and reconciliation remain challenging. However, the various disciplines that pursue different methodological approaches to urban carbon flux assessment have different 1) definitions of uncertainty, 2) needs for attribution, and 3) criteria for successful mitigation guidance. Hence, some disagreement exists over specific policy application and utility.

Estimated likelihood of impact or consequence, including short description of basis of estimate

Continued integration and reconciliation of urban carbon fluxes are likely to achieve methodologically consistent and agreed-on approaches, results of which will be useful for trend detection and mitigation guidance. Assessment of enacted policy has received limited study, and thus the ability to independently assess atmospheric trends and use that information to inform mitigation progress and potential is highly important and relevant to urban carbon mitigation and climate policy.

Summary sentence or paragraph that integrates the above information

For Key Finding 3, the research community recently has begun to integrate and reconcile multiple approaches to urban carbon flux assessments for intensive study sites of urban carbon in North America. These efforts are ongoing but remain challenging due to methodological differences, methodological uncertainties, and differing disciplinary perspectives and criteria. The relevance and importance of these efforts are high because there remains limited independent assessment of urban carbon mitigation efforts or progress.

KEY FINDING 4

Improvements in air quality and human health and the reduction of the urban heat island are important co-benefits of urban carbon emissions mitigation (*high confidence, very likely*).

Description of evidence base

Numerous studies contribute to Key Finding 4, including research on the impacts of carbon emissions reductions on local air pollution, related human health benefits, and reduction of waste heat discharge (Harlan and Ruddell 2011; Huang et al., 2013; Jacobson and Ten Hoeve 2012; Milner et al., 2012; Ostro et al., 2011; Sarofim et al., 2016; Viguié and Hallegatte 2012).

Major uncertainties

Uncertainties include the precise magnitude of health and environmental benefits associated with reductions of carbon emissions. Benefits will vary with a number of factors such as urban population sociodemographics, urban meteorology, composition of emissions sources, and energy fuel mix. Tradeoffs require further research and remain uncertain.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is broad agreement about the benefits of reducing carbon emissions. Major uncertainties are related to assessing quantitatively the impacts and precise relationships between carbon emissions reductions and urban health and environmental benefits.

Estimated likelihood of impact or consequence, including short description of basis of estimate

Key Finding 4 is of high impact. The quantitative relationship between carbon emissions reductions and urban health and environmental impacts has direct and important implications for stakeholder decision making associated with urban air quality, urban climate policy, and general urban planning.

Summary sentence or paragraph that integrates the above information

For Key Finding 4, fossil fuel energy systems emit carbon dioxide (CO_2) and methane (CH_4). These systems also result in emissions of local air pollution and heat discharge in urban environments. Hence, reducing fossil fuel dependence can provide co-benefits to human health and environmental impacts associated with urban heat. The net benefit of these related outcomes remains uncertain because of potential tradeoffs and unforeseen outcomes.

KEY FINDING 5

Urban methane (CH_4) emissions have been poorly characterized, but the combination of improved instrumentation, modeling tools, and heightened interest in the problem is defining the range of emissions rates and source composition as well as highlighting infrastructure characteristics that affect CH_4 emissions (*high confidence*).

Description of evidence base

For Key Finding 5, consistent and persistent evidence of under-reported CH_4 emissions was found in Los Angeles, Boston, and Indianapolis (Lamb et al., 2016; McKain et al., 2015; Wong et al., 2016). Other studies report inverted distributions of CH_4 emissions in Los Angeles (75% thermogenic, 20% biogenic; Hopkins et al., 2016) compared with San Francisco (17% thermogenic, 82% biogenic; Jeong et al., 2017). Intensive field surveys of urban natural gas systems in seven cities indicate large variations in CH_4 leakage rates from urban gas distribution infrastructure attributed to differences in pipeline material and age (Hopkins et al., 2016; Jackson et al., 2014; Phillips et al., 2013; von Fischer et al., 2017).

Major uncertainties

The uncertainties in urban-scale CH_4 emissions estimates are not well established because the number of cities where these emissions have been studied is small and the temporal duration of the studies is very limited. While Key Finding 5 is of high confidence for the limited times and numbers of cities represented in the literature, this finding cannot yet be generalized across other North American cities.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

The assessment of confidence is based on a small number of cities where emissions have been studied over a short period of time. The confidence level is based on the results of these studies, which are robust and agreed upon, but this confidence does not necessarily apply across the continent due to the limited number of studies conducted to date.

Summary sentence or paragraph that integrates the above information

For Key Finding 5, urban CH_4 emissions estimates exist for several North American cities. Yet there are discrepancies between these estimates and governmental inventories. As such, further

research is needed to gain a complete understanding of uncertainties and assess the representativeness of these studies.

KEY FINDING 6

Urban areas are important sites for policymaking and decision making that shape carbon fluxes and mitigation. However, cities also are constrained by other levels of government, variations in their sources of authority and autonomy, capacity, competing local priorities, and available fiscal resources (*high confidence*).

Description of evidence base

Thousands of North American cities have joined municipal networks to pursue co-benefits from climate mitigation measures, including benchmarking initiatives. However, many cities do not have authority to dictate fuel sources for their energy supply or for vehicles, nor they do control carbon inputs into products that come into cities. Evidence for Key Finding 6 indicates that municipal carbon emissions mitigation initiatives in the United States vary significantly among states. This variation suggests that state-level policies and characteristics may influence the propensity of cities in their borders (Krause 2011). Jurisdictional barriers that restrict decision making by municipalities may impede change because of a lack of authority over decision making (Tozer 2013).

Major uncertainties

Cities vary in extent and type of innovation, though the precise motivation lacks sufficient evidence to provide a clear understanding of the factors involved. In addition, each country has different governmental arrangements that affect city autonomy; even within states in the same country, these arrangements may vary.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Evidence of the importance of cities is supported by the large proportion of North American anthropogenic carbon emissions (see Key Finding 1). The evidence for the moderated influence over carbon emissions is supported by the mixture of political, economic, and social authority of cities over direct and indirect emissions sources.

Summary sentence or paragraph that integrates the above information

For Key Finding 6, cities are making policies to reduce their carbon emissions, but they also are constrained by many factors that can limit their authority. Moreover, cities vary widely among themselves. An understanding of the limitations in the ability of cities to mitigate their carbon emissions and why certain cities are more proactive than others is still to be developed.

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5 Agriculture

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KEY FINDINGS

1. Agricultural greenhouse gas (GHG) emissions in 2015 totaled 567 teragrams (Tg)[1] of carbon dioxide equivalent (CO_2e)[2] in the United States and 60 Tg CO_2e in Canada, not including land-use change; for Mexico, total agricultural GHG emissions were 80 Tg CO_2e in 2014 (not including land-use change) (*high confidence*). The major agricultural non-CO_2 emission sources were nitrous oxide (N_2O) from cropped and grazed soils and enteric methane (CH_4) from livestock (*very high confidence, very likely*).[3]

2. Agricultural regional carbon budgets and net emissions are directly affected by human decision making. Trends in food production and agricultural management, and thus carbon budgets, can fluctuate significantly with changes in global markets, diets, consumer demand, regional policies, and incentives (*very high confidence*).

3. Most cropland carbon stocks are in the soil, and cropland management practices can increase or decrease soil carbon stocks. Integration of practices that can increase soil carbon stocks include maintaining land cover with vegetation (especially deep-rooted perennials and cover crops), protecting the soil from erosion (using reduced or no tillage), and improving nutrient management. The magnitude and longevity of management-related carbon stock changes have strong environmental and regional differences, and they are subject to subsequent changes in management practices (*high confidence, likely*).

4. North America's growing population can achieve benefits such as reduced GHG emissions, lowered net global warming potential, increased water and air quality, reduced CH_4 flux in flooded or relatively anoxic systems, and increased food availability by optimizing nitrogen fertilizer management to sustain crop yields and reduce nitrogen losses to air and water (*high confidence, likely*).

5. Various strategies are available to mitigate livestock enteric and manure CH_4 emissions. Promising and readily applicable technologies can reduce enteric CH_4 emissions from ruminants by 20% to 30%. Other mitigation technologies can reduce manure CH_4 emissions by 30% to 50%, on average, and in some cases as much as 80%. Methane mitigation strategies have to be evaluated on a production-system scale to account for emission tradeoffs and co-benefits such as improved feed efficiency or productivity in livestock (*high confidence, likely*).

6. Projected climate change likely will increase CH_4 emissions from livestock manure management locations, but it will have a lesser impact on enteric CH_4 emissions (*high confidence*). Potential effects of climate change on agricultural soil carbon stocks are difficult to assess because they will vary according to the nature of the change, onsite ecosystem characteristics, production system, and management type (*high confidence*).

Note: Confidence levels are provided as appropriate for quantitative, but not qualitative, Key Findings and statements.

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[1] Excludes emissions related to land use, land-use change, and forestry activities.

[2] Carbon dioxide equivalent (CO_2e): Amount of CO_2 that would produce the same effect on the radiative balance of Earth's climate system as another greenhouse gas, such as methane (CH_4) or nitrous oxide (N_2O), on a 100-year timescale. For comparison to units of carbon, each kg CO_2e is equivalent to 0.273 kg C (0.273 = 1/3.67). See Box P.2, p. 12, in the Preface for more details.

[3] Estimated 95% confidence interval lower and upper uncertainty bounds for agricultural greenhouse gas emissions: –11% and +18% (CH_4 emissions from enteric fermentation) and –18% and +20% and –16% and +24% (CH_4 and N_2O emissions from manure management, respectively; U.S. EPA 2018).

5.1 Introduction and Historical Context

Agricultural production is a fundamental activity conducted on 45% of the U.S. land area, 55% of Mexico's land area, and 7% of Canada's land area (World Bank 2016). Because of this vast spatial extent and the strong role that land management plays in how agricultural ecosystems function, agricultural lands and activities represent a large portion of the North American carbon budget. Accordingly, improved quantification of the agricultural carbon cycle, new trends in agriculture, and added opportunities for emissions reductions provide a critical foundation for considering the relationships between agriculture and carbon cycling at local, regional, continental, and global scales. More than 145 countries have specifically included agriculture in their targets and actions for mitigating climate change (FAO 2016), and agriculture has featured particularly prominently in recent target and action commitments made by developing countries to reduce greenhouse gas (GHG) emissions (Richards et al., 2015).

Conversion of vast native forest and prairie to agriculture across North America between 1860 and 1960 resulted in carbon dioxide (CO_2) fluxes to the atmosphere from biota and soils that exceeded those from fossil fuel emissions over the same period (Houghton et al., 1983). Correspondingly, soil organic carbon (SOC) declined in many soils during the 50 years following conversion from native ecosystems to production agriculture (Huggins et al., 1998; Janzen et al., 1998; Slobodian et al., 2002). Crop yields and corresponding above- and belowground biomass have steadily increased since the 1930s due to genetic and management innovations, which provide more organic input from which to build SOC (Johnson et al., 2006; Hatfield and Walthall 2015). This, coupled with improved input-use efficiencies may reduce GHG-emissions per unit yield (GHG intensity), with additional improvements possible through management optimization (Grassini and Cassman 2012; Pittelkow et al., 2015). Options include reducing tillage, integrating perennials onto the landscape, reducing or eliminating bare-fallow land (i.e., land without living plants), adding cover crops, and enrolling lands in conservation easement programs. These options, originally proposed to control erosion, have potential co-benefits in terms of increased soil health, plant productivity, and soil carbon stabilization (Lehman et al., 2015). Conversely, returning lands previously enrolled in conservation easements (e.g., the Conservation Reserve Program [CRP] and other land set-aside efforts) to row-crop production, tillage, or aggressive harvesting of crop residues all risk degrading soil quality and exacerbating SOC loss. Of note is that the net results of land use and land management practices in an agricultural setting vary according to many factors, such as crop or production system type, soil type, climate, and the collection of practices at any given site. For example, many traditional practices followed by Indigenous people on tribal lands are based on an integrated approach to natural resource management and response to environmental change that may provide agricultural options uniquely suited to varied environmental settings (see Ch. 7: Tribal Lands, p. 303).

Agricultural land in the United States totaled 408.2 million hectares (ha) in 2014, of which 251 million ha were in permanent meadows and pastures, 152.2 million ha were in arable land, and 2.6 million ha were in permanent crops (FAOSTAT 2016). Compared with the distribution in 2007, these numbers reflect a 4.7 million ha decline in total agricultural lands, driven by declines in arable land and permanent crops but partially offset by a modest increase in permanent meadows and pastures. Although arable lands have been declining, the combined acreage of the four major crops (corn, wheat, soybeans, and cotton) has risen slightly, with increases in land planted in corn and soybeans and decreases in cotton and wheat (see Figure 5.1, p. 232). Despite the overall slight decline in agricultural land area, the value of U.S. agricultural production rose over the past decade as a result of increased production efficiency and higher prices (USDA 2017a; see also www.ers.usda.gov). Canada has about 65 million ha of agricultural land, of which

about 46 million ha are arable, accounting for only about 7% of the country's total land area (FAOSTAT 2017). Prominent crops on Canada's arable lands include cereals (e.g., wheat, barley, and maize), oilseeds (e.g., canola and soybeans), and pulses (e.g., peas and lentils). Natural and seeded pastures available for grazing in Canada make up about 20 million ha (Legesse et al., 2016). Agricultural land in Mexico makes up 107 million ha, of which 23 million ha are arable land, 2.7 million ha are permanent crops, and 81 million ha are permanent meadows and pastures (FAOSTAT 2017). Mexico's major crops are fruits, corn, grains, vegetables, and sugarcane.

5.2 Societal Drivers and Carbon Management Decisions

A number of social and economic factors drive CO_2 and other GHG emissions associated with agriculture (see Table 5.1, p. 233), including dietary preferences and traditions; domestic and global commodity markets; federal incentives for conservation programs; and technical capabilities for production, processing, and storage in different geographic regions. For example, policies and economic factors that influence bioenergy and biofuel feedstock production systems have diverse direct and indirect impacts on the carbon cycle as discussed later in this chapter and in Ch. 3: Energy Systems, p. 110. A biofuel's carbon footprint depends on the feedstock and its associated management as well as the efficiency of the eventual energy produced from the feedstock. Changes in the management of these social and economic factors can affect soil carbon sequestration and storage and agricultural GHG emissions. Another driver of changes in agricultural production systems is consumer demand for types of food (e.g., meat versus dairy versus vegetable) and provenance of food (e.g., grass-fed, organic, and local). Such influences can have both negative and positive effects on the carbon cycle in direct and indirect ways (see Box. 5.1, Food Waste and Carbon, p. 234). Decision support tools have been developed over the last decade to address agricultural impacts on climate and environmental drivers that play a role in the carbon cycle (for examples, see Ch.18: Carbon Cycle Science in Support of Decision Making, p. 728).

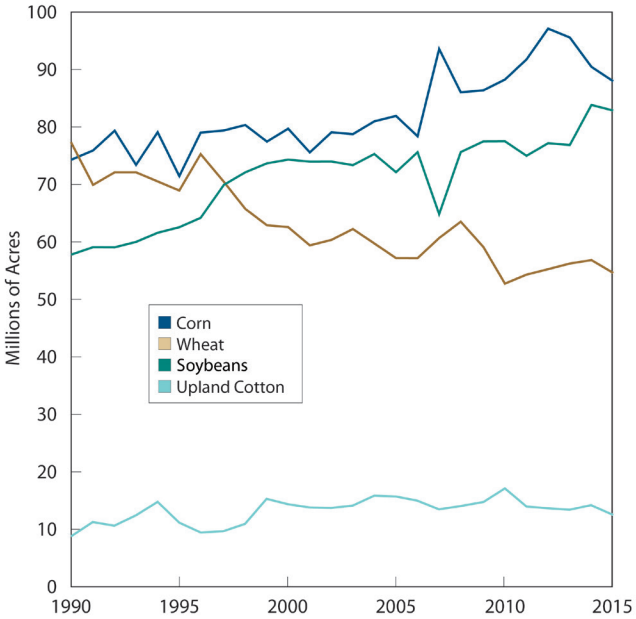

Figure 5.1. U.S. Planted Area for Corn, Wheat, Soybeans, and Upland Cotton, 1990 to 2015. (1 acre = 0.404686 hectares). [Figure source: Adapted from U.S. Department of Agriculture Economic Research Service, baseline related historical data.]

5.3 Current State of the Agricultural Carbon Cycle

Agricultural land carbon storage and loss are the net result of multiple fluxes including plant photosynthetic uptake (i.e., atmospheric CO_2 capture by plants), ecosystem respiratory loss (i.e., carbon released as CO_2 from plants and soil organisms), harvested biomass removal either by grazing or cutting, input from additional feeds, enteric methane (CH_4) production by livestock, and the return of manure by grazing animals or addition of manure or other carbon-rich fertilizer amendments to agricultural lands.

5.3.1 Perennial Systems

The most extensive perennial systems in North America are grasslands, pasture, and hayed lands (see Ch. 10: Grasslands, p. 399). Other perennial

Table 5.1. Greenhouse Gas Fluxes from North American Agriculture (Teragrams of Carbon Dioxide Equivalent per Year)

Emission Source	Canada[a]	United States[b]	Mexico[c]	Total by Source
Enteric Fermentation	25	166.5	43.3	234.8
Manure Management	8	84.0	25.7[f]	117.7
Agricultural Soil Management	24[d]	295.0	0	318.0
Rice Cultivation	0	12.3	0.2	12.5
Liming, Urea Application, and Others	3	8.7	7.5[g]	19.2
Field Burning of Agricultural Residues	0	0.4	1.3	1.7
Crop Residues	NR[e]	NR	1.9	1.9
Total by Country[h]	60	566.9	79.9	705.8

Notes

a) Source: ECCC (2018); data for 2016.
b) Source: U.S. EPA (2018); data for 2015.
c) Source: FAOSTAT (2017); average data for 1990–2014.
d) Includes emissions from field burning of agricultural residues.
e) Not reported.
f) Includes manure applied to soils, manure left on pasture, and manure management.
g) Synthetic fertilizer.
h) As reported in source; may not match sum of individual emission categories due to rounding.

crops (i.e., crops growing and harvested over multiple years) of regional importance include tree crops (mostly fruit and nuts) and vineyards. Because many perennial fruit, nut, and vegetable systems generally are intensively managed, the type of management—such as cover crops and intercropping, irrigation and tillage, fertilizer use, and intensity of cultural activities—largely determines the carbon balance of these production systems. Additionally, biofuel feedstock crops, including perennial grasses and short-rotation woody crops, occupy a very small percentage of agricultural land area, but they have the potential to either sequester carbon or create a carbon debt, depending on the system and land use that the system replaced (e.g., Adler et al., 2007, 2012; Mladenoff et al., 2016). Although differences in net carbon and GHG balance do exist, perennial bioenergy crops generally increase soil carbon in lands converted from annual crops because below-ground carbon allocation (to roots) increases once the crops are established, even though the biomass is harvested for energy (Anderson-Teixeira et al., 2013; Valdez et al., 2017). However, managing perennials as biofuel crops often requires additional nitrogenous fertilizer, which can increase nitrous oxide (N_2O) emissions and reduce the associated mitigation potential (Johnson and Barbour 2016; see Ch. 3: Energy Systems, p. 110).

Perennial systems avoid the 4- to 8-month fallow period common among many annual row-crop systems (Drinkwater and Snapp 2007); therefore, perennial plants can use the sun's energy to drive photosynthesis outside the typical growing season (Baker and Griffis 2005), contributing to increased soil carbon sequestration as compared to annual systems (Sainju et al., 2014). In agricultural systems dominated by perennial plants, photosynthesis generally, but not always, exceeds ecosystem respiration, so on balance these ecosystems remove more CO_2 from the atmosphere than they contribute each year (Gilmanov et al., 2010). The total net amount of CO_2 exchanged between perennial systems and the atmosphere varies among regions, with net carbon loss occurring most often in drought-prone and desert systems (Liebig et al., 2012). In grazed ecosystems, better management practices, such as prescribed grazing, adaptive multipaddock grazing,

Box 5.1 Food Waste and Carbon

Over the past decade, several analyses have pointed to the magnitude of carbon and greenhouse gas (GHG) emissions associated with food waste and food choices and described opportunities to help minimize GHG emissions by reducing food waste, changing diets, and mitigating agricultural emissions (FAO 2013; Foley et al., 2011; Gunders 2012; Gustavsson et al., 2011; Hall et al., 2009; Heller and Keoleian 2015; Hristov et al., 2013b; Parfitt et al., 2010; Vermeulen et al., 2012). Globally, about 1,300 teragrams (Tg) of food per year, or one-third of food produced for human consumption, is lost or wasted. This loss represents production on about 1.4 billion hectares (ha) of land, roughly 30% of the global agricultural area (FAO 2013). On a per-person basis, food loss and waste in North America is 375 to 500 kilograms per year (FAO 2013; Garnett et al., 2013; Gustavsson et al., 2011; Heller and Keoleian 2015), and in the United States and Canada, most of the carbon lost to the atmosphere that is associated with this waste occurs during postprocessing (Bahadur et al., 2016; Porter et al., 2016; Smil 2012). Patterns of food waste in Mexico are less well documented. Public awareness; improved packaging techniques and materials; and improved coordination among producers, manufacturers, and retailers can reduce food waste and its associated carbon emissions (Garnett et al., 2013).

improved grass species and introduction of legumes, fertilization, and irrigation, generally will increase soil carbon sequestration (Conant et al., 2001; Teague et al., 2013). Estimates of the potential for U.S. pasture and hayed lands to sequester carbon (with improved management) vary, ranging from near 0 to 3 or more megagrams of carbon (Mg C) per hectare per year, with reasonable mean values of up to about 0.5 Mg C per hectare per year (Conant et al., 2001).

When productivity increases in agricultural systems, land managers frequently remove more aboveground biomass. In some cases, this increase in carbon removal by harvesting offsets the amount of carbon that would otherwise be sequestered, but the main driver of soil carbon sequestration is the production of belowground biomass that is not removed from the field. As a result, increased forage productivity often is associated with increased soil carbon sequestration (Allard et al., 2007; Ammann et al., 2007; Cong et al., 2014; Skinner and Dell 2016) because increased aboveground biomass normally is associated with increased belowground biomass. Initial conditions and ecosystem characteristics influence carbon sequestration potential. Depleted soils likely will accumulate additional carbon, whereas soils in which carbon inputs and outputs are roughly equal will show no change or perhaps a net loss of carbon over time (Smith 2004). Grazed pastures typically sequester more soil carbon than hayed land (Franzluebbers and Stuedemann 2009; Franzluebbers et al., 2000; Senapati et al., 2014) because cutting can cause a greater initial reduction and slower recovery in photosynthetic uptake of carbon than grazing (Skinner and Goslee 2016). Perennial root systems also become active early and remain active late in the growing season and thus can take up and use reactive nitrogen before it is lost from the system. The capture and efficient use of nitrogen (e.g., nitrate and ammonia applied at the correct time and rates) can avoid nitrogen losses. As a result, N_2O emissions for perennial systems are typically much lower than those for annual systems (Ma et al., 2000; Qin et al., 2004; Robertson and Vitousek 2009).

5.3.2 Annual Systems

As with perennial systems, carbon storage or loss in annually cropped lands is the net result of inputs from unharvested plant residue (especially below

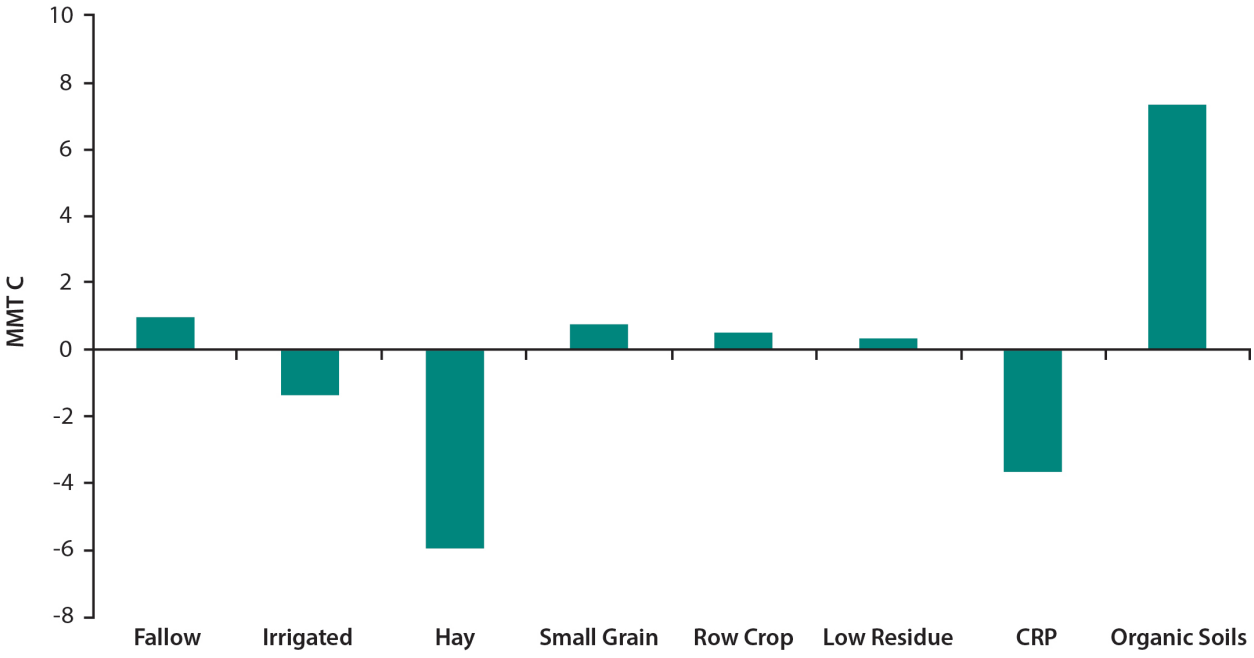

Figure 5.2. Soil Carbon Fluxes for Major Cropping Systems in the United States. Values, in million metric tons of carbon (MMT C), are annual means from 2003 to 2007. Positive values represent net carbon emissions from the system to the atmosphere, and negative values represent net carbon emissions from the atmosphere to system. Categories are mutually exclusive, and not all cropped land is included. Category definitions are based on the majority land use over the 5-year time period. For example, if a land parcel was cropped with maize or soybeans for at least 3 out of the 5 years, it was placed in the row-crop category. Similarly, if a land parcel was crop free during the growing season for at least 3 years, it was placed in the fallow category. Key: CRP, U.S. Department of Agriculture Conservation Reserve Program. [Data source: Del Grosso and Baranski 2016.]

ground); root exudation and turnover; organic matter deposition; soil amendments such as manure; and losses from respiration, residue, leaching, soil organic matter mineralization (decomposition), and harvested biomass removal. In turn, these input and output pathways respond to previous and current land use, soil properties (e.g., soil type and depth), climate, and other environmental factors. Typically, annual cropping systems are managed intensively; as such, their associated carbon stocks are closely related to land management choices (e.g., tillage, crop and crop rotation, residue management, fertilizer and nutrient inputs, extent and efficiency of drainage, and irrigation and use of cover crops) and the duration of those practices.

Studies to date suggest that annually cropped mineral soils in the United States sequester a small amount of carbon, but carbon emissions from cropped organic soils and a number of other farm management practices largely offset this benefit (Del Grosso and Baranski 2016; U.S. EPA 2016; see Figure 5.2, this page). Cropped organic soils (e.g., Histosols) comprise only a small portion (<1%) of overall U.S. cropland, but these organic soils can be a large source of atmospheric carbon on a per area basis. This carbon loss occurs because cropped organic soils commonly result from draining wetlands, which greatly enhances decomposition rates in these high-carbon soils that, historically, have been under water and relatively safe from decomposition. Reversion of these drained and cropped organic soils to wetlands or flooded rice production slows the soil carbon losses but also can result in increased CH_4 and N_2O emissions, implying that water management can play a key role in the

net carbon and GHG balances (Bird et al., 2003; Deverel et al., 2016; Oikawa et al., 2017). However, N_2O does not necessarily increase with land-use conversion to paddy rice because there is evidence of N_2O uptake by recently converted upland crops to flooded rice (Ye and Horwath 2016). Other practices that tend to lead to carbon loss include leaving land fallow without vegetation, growing low-residue crops (e.g., cotton), and plowing intensively (USDA 2014). Conversely, several practices may increase soil carbon stocks, such as including hay and grass in annual crop rotations, growing cover crops, maintaining plant cover, reducing the fallow (vegetation-free) period by increasing cropping intensity especially on marginal land as encouraged by CRP, and possibly reducing tillage intensity (USDA 2014). This increase in soil carbon stocks can vary by ecosystem but is particularly prevalent where these practices are used on soils previously depleted of their original carbon stores.

Compared to perennial crops, annual crop systems tend to have higher nitrogen losses, including N_2O emissions. In addition, nitrogen fertilizer additions generally lead to increased CH_4 emissions and decreased CH_4 oxidation from soils, particularly under anoxic conditions or flooded soil systems such as rice (Liu and Greaver 2009).

5.3.3 Livestock Systems

The North American livestock sector currently represents a significant source of GHG emissions, generating CO_2, CH_4, and N_2O throughout the production process. Livestock contributions to GHG emissions occur either directly (e.g., from enteric fermentation and manure management) or indirectly (e.g., from feed-production activities and conversion of forest into pasture or feed crops).

Enteric Fermentation

Methane and CO_2 are natural end-products of microbial fermentation of carbohydrates and, to a lesser extent, amino acids in the rumen of ruminant animals and the hindgut of all farm animals. Methane is produced in strictly anaerobic conditions by highly specialized methanogenic microbes. In ruminants, the vast majority of enteric CH_4 production occurs in the rumen (i.e., the largest compartment of the ruminants' complex stomach); rectal emissions account for about 3% of total enteric CH_4 emissions (Hristov et al., 2013b). Methanogenic microbes inhabit the digestive system of many monogastric and nonruminant herbivore animals (Jensen 1996). In these species, CH_4 is formed by processes like those occurring in the rumen and is similarly increased by intake of fibrous feeds. Summarizing published data, Jensen (1996) estimated that a 100-kg pig produces about 4.3% of the daily CH_4 emissions of a 500-kg cow. Nonruminant herbivore animals such as horses consume primarily fibrous feeds and emit greater amounts of CH_4 than nonruminant species that consume primarily nonfibrous diets, but a horse's CH_4 production per unit of body weight is still significantly less than that of ruminants. Wild animals, specifically ruminants (e.g., bison, elk, and deer), also emit CH_4 from enteric fermentation in their complex stomachs or the lower gut. The current contribution of wild ruminants to global GHG emissions is relatively low (Hristov 2012).

The U.S. Environmental Protection Agency (EPA) reports that CH_4 emissions from enteric fermentation and manure management amounted to about 232.8 teragrams (Tg) per year CO_2e (functionally equivalent to 63.5 Tg C) in 2015, with an additional 17.7 Tg per year CO_2e (4.8 Tg C) as N_2O emitted from manure management (U.S. EPA 2018). Combined, these emissions represented 3.8% of total U.S. GHG emissions. About 97% of the enteric fermentation and 57% of the CH_4 emissions from manure management were from beef and dairy cattle; 78% of the N_2O emissions from manure management also were attributed to beef and dairy cattle. These estimates are derived from a "bottom-up" approach that begins with estimates of emissions on a per-animal basis and multiplies those estimates over total relevant numbers of animals. "Top-down" approaches, based on measurements of changes in GHG concentrations over large areas and inferences about the sources of those changes, yield different estimates for CH_4 emissions. Combining

satellite data and modeling, several studies proposed that livestock emissions may range from 40% to 90% greater than EPA estimates (Miller et al., 2013; Wecht et al., 2014). There is more uncertainty in predicting CH_4 emissions from manure, partially because these emissions depend heavily on the particular manure handling system and temperature. The sources of discrepancy between the top-down and bottom-up approaches need to be identified to derive accurate estimates for both total and livestock CH_4 emissions in North America (NASEM 2018).

There is no disagreement, however, that cattle are a significant source of CH_4 emissions. Based on U.S. EPA (2018) estimates, CH_4 emissions from cattle make up 25.9% of total U.S. CH_4 emissions if only enteric emissions are counted, or 36.2% if emissions from manure management are included. In a national life cycle assessment of fluid milk, 72% of GHG emissions associated with milk production occurred on the farm, with 25% being from enteric CH_4 fermentation. The remaining 28% was associated with processing, packaging, distribution, retail, and consumers (Thoma et al., 2013). A similar life cycle assessment of beef indicates that 87% of GHG emissions associated with beef are from cattle production, with only 13% resulting from post-farm processes (Asem-Hiablie et al., 2018). Similar to ruminants, animal production is the main contributor of GHG emissions in the swine industry. A life cycle assessment of the U.S. pork industry (Thoma et al., 2011) reported the following breakdown of emission contributions for each stage of the production cycle: 9.6%, sow barn (including feed and manure management); 52.5%, nursery-to-finish (including feed and manure handling); 6.9%, processing (including 5.6% for processing and 1.3% for packaging); 7.5%, retail (e.g., electricity and refrigerants); and 23.5%, the consumer (e.g., refrigeration, cooking, and CH_4 from food waste in landfills). Major sources of GHG emissions in the poultry industry differ depending on the type of production. For broilers (i.e., meat-producing birds), feed production contributes 78% of the emissions; direct on-farm energy use, 8%; post-farm processing and transport of meat, 7%; and manure storage and processing, 6%. For layers (i.e., egg-producing birds), feed production contributes 69% of emissions; direct on-farm energy use, 4%; post-farm processing and transport, 6%; and manure storage and processing, 20% (MacLeod et al., 2013).

Manure Management

Manure can be a major source of GHG emissions, depending on the type of livestock. For ruminants, manure emissions normally are less than those from enteric production, but for nonruminants, manure is the major source of GHG emissions. Microbial activity breaks down organic carbon in manure, releasing both CH_4 and CO_2, and the amount of each produced is related to oxygen availability. Much of the carbon in manure eventually ends up in the atmosphere in one of these two forms, and because CH_4 is a more powerful GHG than CO_2, converting this biogenic carbon to CO_2 would be beneficial.

Methane emissions from all manure produced and handled in the United States were estimated to be 66.3 Tg CO_2e in 2015 (U.S. EPA 2018). These emissions occur in the housing facility, during long-term storage, and during field application (see Table 5.2, p. 238). The housing facility usually is a relatively small source. Manure lying on a barn floor or open-lot surface is exposed to aerobic conditions where CH_4 emissions are low (IPCC 2006; USDA-ARS 2016). Manure deposited by grazing animals also is exposed to aerobic conditions, with CH_4 emissions similar to those from a barn floor or open lot. When manure in the housing facility is allowed to accumulate in a bedded pack up to a meter deep, anaerobic conditions develop, leading to greater CH_4 emissions (IPCC 2006).

Long-term storage normally is the major source of carbon emissions from manure (see Table 5.2). Liquid or slurry manure typically is stored for 4 to 6 months prior to cropland application. During storage, anaerobic conditions are maintained in which CH_4 formation and emission rates are largely controlled by manure temperature (IPCC 2006; USDA-ARS 2016). Longer storage periods

Table 5.2. Estimated Methane Emissions from Livestock Manure Sources in the United States

Species	Portion Lost from Each Farm Source (%)[a]			Total Emissions[b] (Teragrams of Carbon Dioxide Equivalent)
	Housing Facility	Long-Term Storage	Field Application and Grazing	
Dairy Cattle	15 to 20	70 to 80	5 to 10	34.8
Swine	10 to 15	80 to 90	1	24.6
Poultry	45 to 55	45 to 55	1	3.4
Beef Cattle	10 to 15	15 to 20	60 to 70	3.1
Horses	5	35	60	0.2
All Other	5	35	60	0.1
Total	15 to 18	70 to 80	5 to 10	66.3

Notes

a) Estimated from emissions factors (IPCC 2006) and experience with the Integrated Farm System Model (USDA-ARS 2016) and assumed common manure management practices for each species.

b) From U.S. EPA (2018); 2015 emissions data.

will produce greater emissions. Manure solids can float to the surface, particularly in slurry manure, where a crust is formed. This natural crust can reduce storage CH_4 emissions by 30% to 40% (IPCC 2006; USDA-ARS 2016). Solid manure may be stored up to several months in a stack with or without active composting. This type of storage maintains more aerobic conditions, which reduce CH_4 emissions.

Following storage, manure typically is applied to cropland as a nutrient source for plant growth. During unloading from storage and field application, any CH_4 remaining in the manure is released. These emissions are small compared to those from other sources. Following application of the manure spread onto the soil in a thin layer, aerobic conditions suppress further CH_4 production. Manure also may be incorporated into the soil so that any CH_4 produced is oxidized and consumed (Le Mer and Roger 2001). Thus, optimizing the timing, quantity, and incorporation of manure applications with plant productivity and growth patterns and needs can reduce the associated CH_4 and N_2O emissions.

5.4 Indicators, Trends, and Feedbacks

5.4.1 Trends in Acres Cultivated, Soil Carbon, and Overall Emissions

The *First State of the Carbon Cycle Report* (CCSP 2007) showed total agricultural and grazing lands in North America (e.g., cropland, pasture, rangeland, shrub lands, and arid lands) accounting for 17% of global terrestrial carbon stocks. Most of this carbon pool existed within soils; less than 5% resided in cropland vegetation. More recent data estimate that the annual U.S. soil carbon sequestration rate decreased between 1990 and 2013, primarily due to changes in land use and variability in weather patterns. Worth noting are the large interannual fluctuations in the size of the mineral soil CO_2 sink (USDA 2016). The major non-CO_2 emissions from U.S. agriculture in 2013 were N_2O from cropped and grazed soils (44% of U.S N_2O emissions) and enteric CH_4 from livestock (28% of U.S. CH_4 emissions). In 2015, the major non-CO_2 emissions from U.S. agriculture were N_2O from agricultural soil management (52% of all agricultural emissions, or 4.4% of all U.S. GHG emissions) and enteric CH_4

from livestock (29% of agricultural emissions, or 2.5% of all U.S. GHG emissions). Combined with forestry, the agricultural sector contributed to a total net carbon sequestration of 270 Tg CO_2e in 2013 (USDA 2016), while total agricultural GHG emissions (excluding land use, land-use change, and forestry activities) amounted to 567 Tg CO_2e in 2015 (U.S. EPA 2018).

Agricultural GHG emissions in North America were 706 Tg CO_2e in 2014 and 2015 (Table 5.1, p. 233), including 567 Tg CO_2e in the United States (excluding emissions from land use, land-use change, and forestry; U.S. EPA 2018), 59.0 Tg CO_2e in Canada, and 79.9 Tg CO_2e in Mexico (Table 5.1). Agricultural non-CO_2 emissions were primarily N_2O from cropped and grazed soils and CH_4 from enteric fermentation in livestock. In 2014 and 2015, North America's major sources and annual rates of GHG emissions (in CO_2e) included: agricultural soil management (318.0 Tg), enteric fermentation (234.8 Tg), manure management (117.7 Tg), and rice cultivation (12.5 Tg; Table 5.1). Trends that drive North American GHG emissions from agriculture include changes in five areas: 1) the amount of nitrogen fertilizer applied, which correlates with land area planted in corn, cotton, and wheat (USDA 2016); 2) the number of ruminants, especially beef cattle and dairy cows because they produce large quantities of enteric and manure CH_4; 3) trends in human diet choices, which drive changes in land use, numbers of livestock, and volumes of inputs like fertilizer; 4) area of agricultural land opened by clearing forest, which converts large amounts of carbon in plants and soils to CO_2; and 5) the amount of food wasted, which leads to CH_4 emissions from landfills and also drives additional production with associated GHG emissions (e.g., Hall et al., 2009). Overall, actively managed agricultural lands have a strong capacity to reduce GHG emissions to the atmosphere and take up and store carbon. Varying management options thus could lead to substantial reductions in emitted CO_2 and CH_4 and sequester significant amounts of carbon.

According to the U.S. 2012 Agricultural Census, 370 million ha were classified as farmland (see Table 5.3, p. 240). Such lands declined by 3.1 million ha between 2007 and 2012 (USDA-NASS 2012). Out of the converted croplands, 18% changed to nonagricultural uses (e.g., urban growth and transportation); another 3% reverted to forest; and the remaining 79% were used for other types of agricultural land, primarily pastures (USDA-NRCS 2015). The conversion of farmland to other uses appears to have slowed compared with the period from 2002 to 2007, when greater than 9.6 million ha of farmland were converted to other uses (USDA-NASS 2012). In 2012, 19% of the total 786.8 million ha in the contiguous 48 states, Hawai'i, Puerto Rico, and the U.S. Virgin Islands was classified as cropland, 1% as CRP, 6% as pastureland, and 21% as rangeland (USDA-NRCS 2015).

Similar to these trends in North America, global GHG emissions from large ruminants, such as beef and dairy cattle, are about seven times greater than emissions from swine or poultry (Gerber et al., 2012). Dairy production systems, however, are considerably more efficient than beef systems. As an example, Eshel et al. (2014) estimated, using a full life cycle assessment, that GHG emissions per human-edible megacalorie (MCal) were 9.6 kg CO_2e for beef versus 2 for pork, 1.71 for poultry, and 1.85 for dairy. Similarly, GHG emissions per kg of human-edible protein were 214 kg CO_2e for beef, 42 for pork, 20 for poultry, and 32 for dairy (Eshel et al., 2014).

U.S. cattle inventories have fluctuated during the last several decades from a peak of over 130 million heads (both beef and dairy) in the 1970s to a low of 88.5 million in 2014. Cattle numbers increased to 89 million in 2015 and an estimated 92 million in 2016 (USDA-NASS 2016). According to the 2016 inventory, there were 30.3 million beef cows, 9.3 million dairy cows, 19.8 million heifers weighing 227 kg or more, 16.3 million steers at 227 kg or more, 14 million calves under 227 kg, and 2.1 million bulls. Beef and dairy cows, because of their high feed consumption and higher-fiber diets, are the largest emitters of enteric CH_4, producing about 95 and

Table 5.3. United States Agricultural Lands by Sector and Percentage of Cropland Reportedly Managed with Conservation Practice and Distribution of Crops and Managements[a]

Land	Acreage (Million Hectares)	No Till (%)[b]	Other Conservation Tillage (%)	Cover Crop	Conservation Easement
Total Agricultural Lands 2012	370.1				
Cropland[c]	157.7	24	19.67	2.41	3.38
Pasture	49	NA[d]			
Rangeland (Includes Federal and Nonfederal Lands)	246.7				
Conservation Reserve Program	1.5				
Crop	**Acreage (Million Hectares)**	**Percentage of Cropland**	**Managed Under No Till or Strip Till (%)[e]**		
Corn	38.3	24.3	31		
Soybeans	30.8	19.5	46		
Wheat	19.8	12.6	33		
Cotton	3.8	2.4	43		
Sorghum	1.1	1.6	NA		
Rice	1.1	0.7	NA		
Hay[f]	22.8	14.4	NA		

Notes

a) The percentage of no-tilled land does not imply that these lands are managed in a long-term, no-till system.
b) Duration of no-till practice is not available; this value does not necessarily reflect a continuous practice.
c) USDA-NASS (2012).
d) Not applicable.
e) Wade et al. (2015).
f) USDA-NRCS (2015).

146 kg CH_4 per head per year, respectively; emissions from feedlot cattle fed high-grain diets are considerably less at 43 kg per year per head (U.S. EPA 2018). Increased cattle productivity has resulted in increased feed efficiency and decreased enteric CH_4 emission intensity (i.e., CH_4 emitted per unit of milk or meat). As an example, the estimated CH_4 emission intensity for the U.S. dairy herd has decreased from 31 g per kg milk in 1924 to 14 g per kg in 2015 (Global Research Alliance on Agricultural Greenhouse Gases 2015).

Cattle inventories in Canada have fluctuated annually, but long-term trends are relatively stable—about 12 million heads in January 2016, down slightly from a peak in 2005 (Statistics Canada 2016). Beef cattle account for more than 80% of these animals. In recent decades, improvements in management efficiency have led to a decline in GHG emissions per unit of livestock product. For example, estimated emissions per kilogram of liveweight beef leaving the farm declined from 14 kg CO_2e in 1981 to 12 kg CO_2e in 2011 (Legesse et al., 2016).

U.S. beef consumption has been declining steadily over the past decade (see Figure 5.3, p. 241) while consumption of dairy products has been increasing (see Figure 5.4, p. 242). The previously mentioned life cycle assessment analyses that found greater

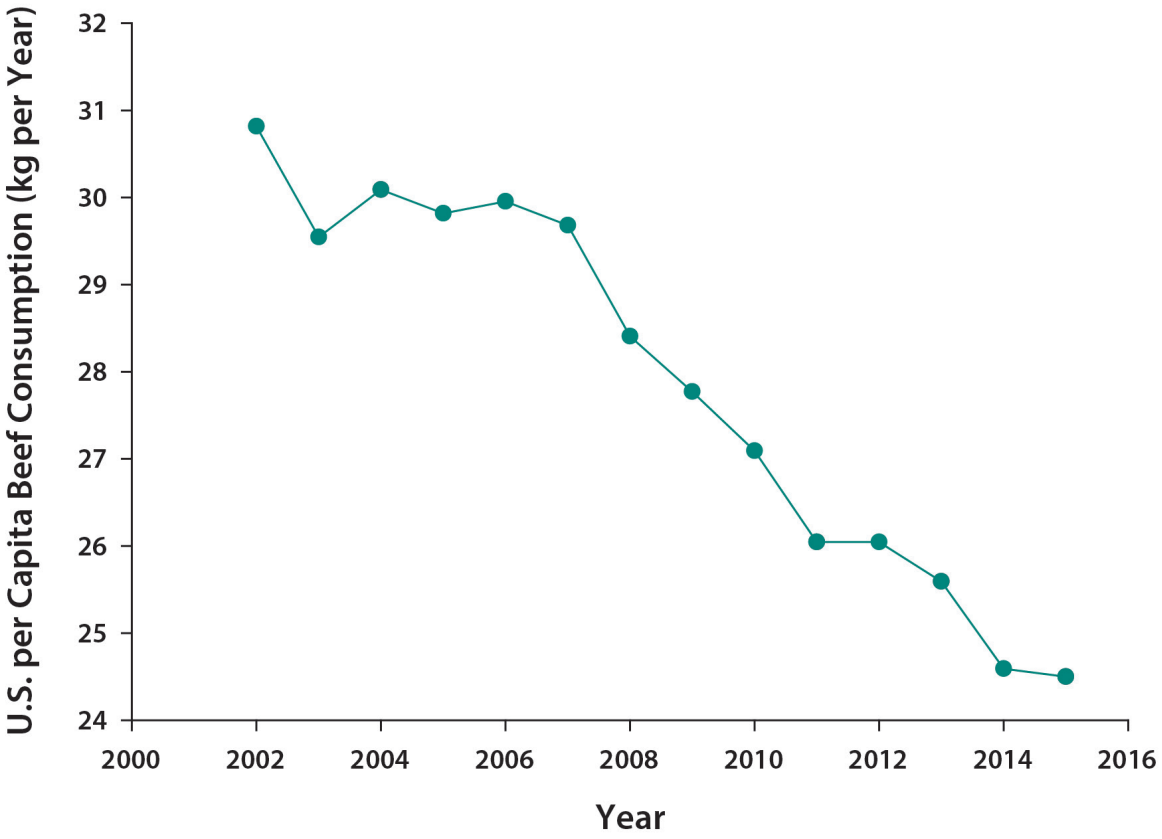

Figure 5.3. U.S. per Capita Beef Consumption. [Data sources: U.S. Department of Agriculture (USDA) National Agricultural Statistics Service and USDA Economic Research Service.]

carbon efficiency of dairy versus beef suggest that this trend should translate to lower emissions from the livestock sector. Most of the beef and veal consumed in the United States was domestically produced (about 86% in 2015; 18.6% of imported beef was from Canada), while about 9.6% of beef produced in the United States in 2015 was exported to other countries. Fluid milk consumption per capita has been decreasing—from about 89 kg per year in 2000 to 71 kg per year in 2015, while consumption of cheese, butter, and yogurt, most of which is domestically produced, has been steadily increasing. As in the United States, per capita consumption of livestock products in Canada also has declined in recent decades. For example, beef and fluid milk consumption decreased from 39 kg of beef per capita in 1980 to 24 kg in 2015 (Agriculture and Agri-Food Canada 2016) and from 90 liters of fluid milk per capita in 1996 to 71 liters in 2015 (Government of Canada 2016).

The strong influence of these carbon-intensive food consumption patterns on the global carbon cycle highlights the challenge of assigning emissions to a particular country. As mentioned previously, 2.5% of beef consumed in the United States is imported from Canada. Most inventories assign these emissions to the country where production occurs, but a main lever that could influence GHG emissions associated with this production rests, in this case, with the United States, because demand is a strong driver of supply and production.

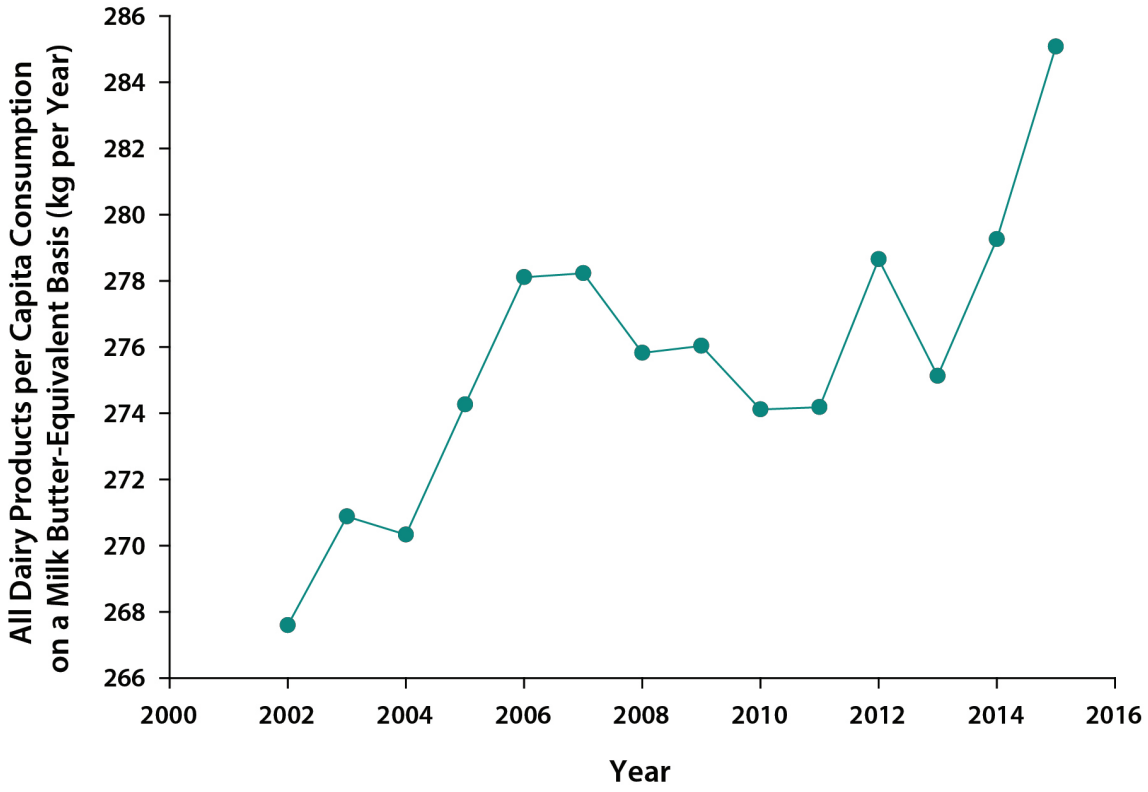

Figure 5.4. U.S. per Capita Total Consumption of Dairy Products. [Data sources: U.S. Department of Agriculture (USDA) National Agricultural Statistics Service and USDA Economic Research Service.]

5.4.2 Climate Change Effects and Feedbacks on Carbon

Climate change, including changes in temperature, precipitation, and the frequency of extreme events, could alter the productivity of agricultural systems through its effects on plant and animal growth as well as carbon sequestration and storage by influencing soil respiration and plant allocation to soil carbon. Climate change also could have an indirect effect on enteric CH_4 emissions (i.e., from ruminant animals) and directly influence manure and soil-derived CH_4 emissions through temperature increases. The effect on enteric emissions is through increased or decreased feed (i.e., dry matter) intake; projected increased ambient temperatures can decrease dry matter intake and thus proportionally reduce enteric CH_4 emissions. As an example, the average maximum temperature for the northeastern United States is projected to increase 6.5°C by 2100 (projected by Representative Concentration Pathway 8.5, a high-emissions scenario). This temperature increase is expected to decrease dry matter intake of dairy cows in the region by an additional 0.9 kg per day due to heat stress (Hristov et al., 2017a). This decreased intake will amount to a reduction in daily enteric CH_4 emissions of about 17 g per cow. If this reduction is extrapolated over 365 days and 1.4 million cows in the northeastern United States, the increased temperature will lead to a decrease in enteric CH_4 emissions from dairy cows of about 8.7 metric tons per year, but the net effect on CO_2e per kg of product depends on the effect of temperature on productivity. In contrast, increased temperatures are expected to increase manure CH_4 emissions. The microbial decomposition of manure, producing

CH_4, is sensitive to temperature, so the projected climate changes suggest an increase in emissions of about 4% by midcentury and 8% by 2100 (Rotz et al., 2016).

Climate change effects on soil carbon sequestration will involve a balancing act between the impacts of elevated CO_2, higher temperatures, and either increasing or decreasing precipitation depending on the region under consideration. Elevated CO_2 and increased precipitation are expected to increase carbon inputs into systems and increase their potential to sequester carbon, whereas higher temperatures are expected to increase ecosystem respiration. Also, yields of major crops (corn, soybeans, wheat, and rice) are predicted to decline as global temperature increases (Zhao et al., 2017). Reduced precipitation or soil moisture along with the drying effects of warming would be expected to decrease plant production and carbon inputs in most upland systems. In unmanaged ecosystems, limited nitrogen availability could constrain the positive effects of elevated CO_2 on plant growth (Norby et al., 2010; Thornton et al., 2007), although in managed pasture and hayland systems, fertilization would be expected to overcome such constraints. Tubiello et al. (2007) suggested that the balance between competing pressures would result in greater crop yields in temperate regions compared with those in semiarid and tropical regions. However, several analyses suggest that increased atmospheric CO_2 will increase soil CO_2 respiration by almost as much as the stimulation of inputs, resulting in little net change in soil carbon pools (Dieleman et al., 2012; Todd-Brown et al., 2014; van Groenigen et al., 2014). Because the potential effects of climate on soil carbon sequestration could be relatively small in most North American agricultural systems, at least compared with the large changes expected in the Arctic (Todd-Brown et al., 2014; see Ch. 11: Arctic and Boreal Carbon, p. 428), management is projected to have a greater effect on carbon sequestration than will changes in climate (Álvaro-Fuentes and Paustian 2011; Lugato and Berti 2008).

5.5 Agriculture's Impact on Atmospheric CO_2

The 2018 EPA inventory (U.S. EPA 2018) attributed 567 Tg CO_2e to the agricultural sector for 2015 (excluding emissions related to land use, land-use change, and forestry activities), accounting for 8.5% of total U.S. emissions.[4] This proportion reflects a small increase since 1990, primarily due to increased CH_4 emissions from manure management. Nitrous oxide emissions from agricultural soil management were the largest sources of GHGs at 295 Tg CO_2e, and these emissions, largely due to synthetic nitrogen fertilizer applications, accounted for 77.7% of all U.S. N_2O emissions. Other sources primarily included enteric fermentation (166.5 Tg CO_2e), manure management (66.3 Tg CO_2e and 17.7 Tg CO_2e as CH_4 and N_2O, respectively), rice cultivation (12.3 Tg CO_2e), field burning (0.4 Tg CO_2e), and CO_2 emissions from urea fertilization and liming (4.9 and 3.8 Tg CO_2e, respectively). Within the enteric fermentation emissions, beef cattle accounted for 70.9% and dairy cattle 25.6%. Worth noting is that these numbers have been relatively stable since 1990 even though production of beef and dairy products has increased. Agricultural croplands remaining as cropland in the United States (i.e., not converted to or from other land uses) represent a small sink sequestering an estimated 0.1% of the CO_{2e} removed from the atmosphere by land use, land-use change, and forestry activities (U.S. EPA 2018). As noted previously, agricultural practices that remove CO_2 from the atmosphere include conversion from cropland to permanent pastures or hay production, reduction in acreage managed with summer fallow, adoption of conservation tillage practices, and increased applications of manure or sewage sludge. Overall, SOC increases in croplands remaining cropland and croplands converted to grasslands collectively offset losses caused by recent conversions of long-term grassland to cropland

[4] Estimated 95% confidence interval lower and upper uncertainty bounds for agricultural GHG emissions: –11% and +18% (CH_4 emissions from enteric fermentation) and –18% and +20% and –16% and +24% (CH_4 and N_2O emissions from manure management, respectively; U.S. EPA 2018).

(U.S. EPA 2015, 2016, 2018; see also Ch. 12: Soils, Section 12.5.1, p. 484).

In Canada, agricultural soils (55.2 million ha) contain about 4.1 petagrams (Pg) C (0- to 30-cm soil depth) and 5.5 Pg C (0- to 100-cm soil depth), as calculated from the Canadian Soil Information Service National Soil Database and reported in Ch. 12: Soils, p. 469. As of 2013, Canadian agricultural land removed 11 Tg CO_2 per year, which would counter about 2% of the total Canadian national GHG emissions (ECCC 2018). The reduction was attributed to decreased summer fallow and increased adoption of no-till practices in Canadian prairies. However, this value is starting to decline (e.g., down from 13 Tg CO_2 in 2005) because changes in SOC stocks and fluxes tend to approach equilibrium at some point after a change in conditions.

5.5.1 Impact of Management Practices

Croplands

Most cropland carbon stocks are in the soil and reflect management history and practices that increase or decrease soil carbon stocks. Integration of practices that can increase soil carbon stocks include 1) maintaining land cover with vegetation (e.g., use of deep-rooted perennials, elimination of summer fallow, and inclusion of cover crops in annual systems); 2) protecting the soil from erosion (e.g., reduced or no tillage and residue cover); and 3) improving nutrient management (Srinivasarao et al., 2015; Swan et al., 2015). The magnitude and longevity of carbon stock changes have strong environmental and regional differences that are subject to subsequent changes in management practices. Conversely, practices that convert lands from perennial systems, such as converting retired or other lands to row crops, consistently show release of stored carbon back to the atmosphere (Gelfand et al., 2011; Huang et al., 2002). Other management practices with the potential to release stored carbon are inadequate return of crop residues (e.g., Blanco-Canqui and Lal 2009), aggressive tillage (Conant et al., 2007), over application of nitrogen fertilizer, and burning of crop residue (Robertson and Grace 2004; Wang et al., 2011).

The timescale for carbon storage in soils is a critical factor for GHG mitigation. Numerous estimates of the rates and potential magnitude of long-term soil carbon accumulation, storage, and sequestration related to management have been reviewed and presented (e.g., Minasny et al., 2017; Paustian et al., 2016; Sperow 2016; Stockmann et al., 2013; Swan et al., 2015). Management practices that increase carbon inputs include planting high-residue crops and returning crop biomass to the soil; minimizing or eliminating summer fallow (particularly bare fallow); adding cover crops to reduce winter fallow; extending and intensifying cropping rotations (e.g., double-cropping or relay cropping and adding forage perennials); retiring marginal lands to perennials; and adding perennials in buffer strips, field borders, filter strips, grassed waterways, vegetative barriers, and herbaceous wind barriers (e.g., Mosier et al., 2006; Paustian et al., 2016; Sainju et al., 2010; Sperow 2016). Swan et al. (2015) estimated carbon storage rates of 0.42 to 0.95 Mg C per hectare per year among conservation practices that shift to perennials (e.g., retiring marginal land or planting perennials as barriers or borders), while inclusion of cover crops was estimated to accrue 0.15 to 0.27 Mg C per hectare per year. Practices that eliminate summer fallow can increase SOC directly by increasing carbon input or modifying microclimate (i.e., temperature and water), a practice that can decrease mineralization rates by reducing temperature and water content (Halvorson et al., 2002; Sainju et al., 2015).

Numerous publications have reported that no-tillage practices store more carbon in soil than those using conventional tillage (e.g., Paustian et al., 2016; Sperow 2016; West and Post 2002). Conversely, others have disputed this claim, especially when including soil carbon measurements deeper than 30 cm (e.g., Baker et al., 2007; Luo et al., 2010; Powlson et al., 2014; Ugarte et al., 2014). No-tillage and other conservation practices were developed to control soil erosion, and this co-benefit is well established. Erosion removes soil carbon from farm fields and relocates that carbon to other parts of the landscape; the amount of this transported carbon that is sequestered in sediments compared to the amount converted to CO_2 or CH_4 is difficult to

estimate (Doetterl et al., 2016). In Ch. 12: Soils, the role of soil erosion is discussed in greater detail and suggests that burial of eroded carbon constitutes a small sink. Comparing SOC sequestration rates from a system managed without tillage to a system with tillage results in negative, neutral, and positive rates of SOC sequestration: 1) 27 ± 19 Mg SOC per hectare per year, (n = 49; Liebig et al., 2005), 2) 0.40 ± 61 Mg SOC per hectare per year (n = 44; Johnson et al., 2005), or 0.45 ± 0.04 Mg SOC per hectare per year (n = 147; Franzluebbers 2010). Likewise, studies using eddy covariance techniques report divergent responses to tillage. For example, Bernacchi et al. (2005) demonstrated that no-tillage agriculture on clay-rich soil built SOC, whereas others (Baker and Griffis 2005; Chi et al., 2016; Verma et al., 2005) used gas exchange techniques to suggest conservation or no-tillage systems were near carbon neutral. In another review, Collins et al. (2012) found that carbon sequestration rates varied from no measurable increase (Staben et al., 1997) to 4 Mg C per hectare per year (Lee et al., 2007), varying with depth monitored, study duration, fertilizer formulation, and location. Several rationales have been postulated for this variability. If sampling depth is shallower than the tillage depth, the apparent change in SOC may be an artifact of sampling depth (Baker et al., 2007) or caused by residue redistribution (Staricka et al., 1991) and vertical stratification of soil carbon (Luo et al., 2010). Meta-analyses by Luo et al. (2010) and Ugarte et al. (2014) suggest that other factors contributing to variability in SOC sequestration include climatic and soil properties interacting with management factors (e.g., cropping frequency, crop rotation diversity, nitrogen, and drainage) along with impacts on rooting depth and above- and belowground biomass, as well as soil heterogeneity and the long time frames required to find a definitive increase or decrease in SOC. Collectively, the evidence indicates that adoption of no tillage may store more carbon, especially in the soil surface, compared to storage with conventional tillage. However, conclusively measuring short-term changes is difficult because of soil heterogeneity and slow rates of change (also discussed in Ch. 12: Soils). In particular, increased N_2O or CH_4 emissions have been shown to occur for as many as 10 years after no-till adoption (Six et al., 2004), though this effect is greater and more consistent in medium to poorly drained soils (Rochette 2008). Thus, quantifying GHG mitigation by management also must account for changes in N_2O and CH_4, which can occur coincidently with changes in soil carbon storage (VandenBygaart 2016).

From a carbon emissions perspective, biofuels have received a great deal of attention because of their potential to produce a more carbon neutral liquid fuel relative to fossil fuels. Biofuels from annual crops currently supply about 5% of U.S. energy use, mostly from corn grain ethanol (~36% of the corn grain harvest) and soy biodiesel (~25 % of the soybean harvest; USDA 2017b). Although the potential for reduced GHG emissions with biofuels is compelling, some life cycle assessment analyses suggest that corn grain ethanol has marginally lower (or even greater) GHG emissions compared with those from fossil fuels (e.g., Del Grosso et al., 2014; Fargione et al., 2008). However, more recent studies suggest that currently available technologies can achieve greater GHG reductions of 27% to 43% compared to gasoline when assessed on an energy equivalent basis (Canter et al., 2015; Flugge et al., 2017). Reasons for reduced net GHG intensity for grain- and oil-based biofuels include improved crop-management practices and diminished emissions from land-use change because most of the yield gap from diverting food and feed crops to biofuel feedstocks has been met by increasing per-unit area yields, taking into account the benefits of co-products (e.g., using dried distiller grains for livestock feed) and implementing more efficient feedstock conversion technologies (Flugge et al., 2017). Typically, cellulosic biomass conversion technologies are considered too expensive to compete with liquid fuels derived from other sources (Winchester and Reilly 2015), but innovations at all levels are advancing conversion technology. The impact of cellulosic biofuels on the carbon cycle (Fulton et al., 2015) will depend on ensuring that appropriate mitigation strategies are followed

during feedstock choice (perennial or annual) and cultivation (e.g., related to soil carbon stock changes [Blanco-Canqui 2013; Johnson et al., 2012, 2014; Qin et al., 2015]), transportation, and conversion to biofuels (U.S. DOE 2016).

Co-Benefits of Conservation Management

Many common conservation practices improve soil aeration, aggregate stability, and nutrient reserves, while modulating temperature and water and increasing microbial activity and diversity. As a result, soil under some conservation-management regimes can be more resilient to climate variability and more productive (Lal 2015; Lehman et al., 2015). For example, adoption of practices that can conserve soil carbon (e.g., perennial crops, cover crops, and no tillage) may reverse the effects of tillage-intense systems associated with environmental and soil degradation (Mazzoncini et al., 2011). Plant material maintained on the soil surface improves soil physical properties (e.g., Johnson et al., 2016), nutrient availability, and microbial biomass and activity (Feng et al., 2003; Weyers et al., 2013). These improvements result in enhanced soil and water quality and soil productivity (Franzluebbers 2008). Cover crops improve soil health by increasing microbial diversity, biomass, and activity (Bronick and Lal 2005; Lehman et al., 2012, 2015; Schutter and Dick 2002); they also improve soil aggregation, water retention, and nutrient cycling (Blanco-Canqui et al., 2013; Drinkwater et al., 1998; Kladivko et al., 2014; Liebig et al., 2005; Sainju et al., 2006). Thus, there are management practices that simultaneously benefit a number of soil health and carbon storage attributes.

5.5.2 Emissions Reduction

Livestock

Enteric fermentation and manure management represent 44% of the 2015 agricultural GHG emissions in the United States (U.S. EPA 2018) and 36% and 58% of the agricultural emissions in Canada and Mexico, respectively (FAOSTAT 2017). Of the total U.S. GHG emissions in 2015, however, emissions from enteric fermentation and manure management made up only 3.8% (U.S. EPA 2018). Methane mitigation practices for livestock include practices related to reducing emissions from enteric fermentation (i.e., cattle) and manure management (i.e., cattle and swine) as discussed by Hristov et al. (2013b) and Herrero et al. (2016). Increasing forage digestibility and digestible forage intake generally will reduce CH_4 emissions from rumen fermentation (and stored manure) when scaled per unit of animal product. Enteric CH_4 emissions may be reduced when corn silage replaces grass silage in the diet. Legume silages also may have an advantage over grass silage because of their lower fiber content and the additional benefit of reducing or replacing inorganic nitrogen fertilizer use. Dietary lipids are effective in reducing enteric CH_4 emissions, but the applicability of this practice will depend on its cost and effects on feed intake, production, and milk composition in dairy cows. Inclusion of concentrate feeds in the diet of ruminants likely will decrease enteric CH_4 emissions per unit of animal product, particularly when the inclusion is above 40% of dry matter intake.

A number of feed additives, such as nitrates, also can effectively decrease enteric CH_4 emissions in ruminants. Because these additives can be toxic to the animals, proper adaptation is critical. However, nitrates may slightly increase N_2O emissions, which decreases their overall mitigating effect by 10% to 15% (Petersen et al., 2015). Through their effect on feed efficiency, ionophores are likely to have a moderate CH_4-mitigating effect in ruminants fed high-grain or grain-forage diets. Some direct-fed microbial products, such as live yeast or yeast culture, might have a moderate CH_4-mitigating effect by increasing animal productivity and feed efficiency, but the effect is expected to be inconsistent. Vaccines against rumen methanogens may offer mitigation opportunities in the future, but the extent of CH_4 reduction appears small, and adaptation and persistence of the effect are unknown. A recently discovered enteric CH_4 inhibitor, 3-nitrooxypropanol, has shown promising results with both beef and dairy cattle. Under industry-relevant conditions, the inhibitor persistently decreased enteric CH_4 emissions by 30% in dairy cows, without negatively affecting animal

productivity (Hristov et al., 2015). Similar or even greater mitigation potential has been reported for beef cattle (Romero-Perez et al., 2015). If its effectiveness is proven in long-term studies, this mitigation practice could lead to a substantial reduction of enteric CH_4 emissions from the ruminant livestock sector.

Animal management also can have an impact on the intensity (i.e., emissions per unit of animal product) of CH_4 emissions from livestock systems. For example, increasing animal productivity through genetic selection for feed efficiency can be an effective strategy for reducing CH_4 emission intensity. Other management practices for significantly decreasing total GHG emissions in beef and other meat production systems include reducing age at slaughter of finished cattle and the number of days that animals consume feed in the feedlot. Improved animal health, reduced mortality and morbidity, and improved reproductive performance also can increase herd productivity and reduce GHG emission intensity in livestock production (Hristov et al., 2013a).

Several practices are known to reduce CH_4 emissions from manure but cannot be considered in isolation of other GHG sources and pollutants such as N_2O and ammonia (NH_3). Practices such as the use of solid manure storage and composting can reduce CH_4 emissions, but N_2O and NH_3 emissions will increase, and the end result may not be a reduction in overall GHG emissions. Mitigation of carbon emissions also may have tradeoffs with other pollutants including other gaseous emissions, nutrient leaching to groundwater, and nutrient runoff to surface waters. For example, eliminating long-term manure storage can greatly reduce CH_4 emissions, but daily spreading of manure throughout the year can cause greater nutrient runoff. Mitigation strategies must be considered from a whole-farm perspective to ensure a net environmental benefit (Montes et al., 2013).

Potential CH_4 mitigation strategies include manure solids separation, aeration, acidification, biofiltration, composting, and anaerobic digestion (Montes et al., 2013). Removal of solids from liquid manure reduces available carbon for methanogenesis, and composting or storing the solids in a stack under more aerobic conditions reduces total CH_4 emissions. For long-term manure storage, covers likely will become mandatory to reduce NH_3, CH_4, and N_2O emissions. Semipermeable covers such as the natural crust on slurry manure or added floating materials such as straw, wood chips, expanded clay pellets, and some types of plastic can reduce CH_4 and NH_3 emissions from storage by 30% to 80%, but they also may increase N_2O emissions. Greater reductions and perhaps near elimination of emissions can be achieved by sealing the cover and using a flare to convert the accumulated CH_4 to CO_2. Anaerobic digesters also can be used to enhance CH_4 production, capturing the produced biogas and using it on the farm to heat water and generate electricity. Extracting the carbon from manure reduces storage emissions, and the reduction in purchased gas and electricity provides other off-farm environmental benefits. Composting solid manure in aerated windrows can greatly reduce CH_4 emissions, but this processing will increase NH_3 and N_2O emissions (Montes et al., 2013).

Experimental processes of acidification and biofiltration show potential for reducing CH_4 emissions if practical and economical systems can be developed (Montes et al., 2013). Decreasing the pH of manure reduces NH_3 and CH_4 emissions, but the cost of the acid, safety in handling, and difficulty in maintaining the low pH all deter its use. Biofiltration can extract CH_4 from ventilation air in barns, but the large size and cost preclude adoption. Biofilters also may create N_2O emissions, offsetting some of the carbon reduction benefits.

Rice Production

Rice emits four to five times more CH_4 and N_2O to the atmosphere (Linquist et al., 2012) and uses two to three times more water per kg than other cereals (Bouman et al., 2007; Tuong et al., 2005). Sustainably oriented production practices have been developed with the goal of mitigating the environmental impact of rice and improving the economic benefits through reductions in production costs. These practices include the irrigation management practice of alternate wetting and drying (AWD) or intermittent

flooding, whereby the soil surface is allowed to dry for several days to a week before rewetting in midseason. This practice can be repeated up to five times during the growing season without reducing harvest yield. The concurrent re-oxygenation of the soil layer keeps CH_4 emissions low, and studies have shown that water-saving irrigation methods such as AWD reduce net CH_4 emissions produced under water-saturated conditions (Linquist et al., 2015; Rogers et al., 2013). Even one 6-day, midseason drainage event, temporarily reducing anaerobic soil conditions, can reduce post-drainage CH_4 emissions by 64% with no evident effect on yield (Sigren et al., 1997). This practice also has the co-benefit of reducing grain arsenic concentrations because it changes the soil reduction-oxidation (redox) potential (Linquist et al., 2015). Other irrigation techniques that reduce the inundated soil period also will reduce the CH_4 emissions from rice paddies. These methods include the use of drill-seeding rather than water-seeding or transplanting rice (Pittelkow et al., 2014) and carry the additional benefit of reducing the pumping requirements of irrigation water; thus, they will reduce GHG production associated with the energy use of burning fossil fuels—whether through diesel or indirectly through electricity generation. The reduced pumping benefits are particularly true in rice production regions of the Midsouth that are distinct from those in California, where irrigation needs are met from gravity-fed reservoirs draining the Sierra Nevada mountains. However, for any CH_4-reducing rice production regime, care must be taken to keep N_2O emissions low. As indicated, rates of N_2O emissions are particularly sensitive to inputs from nitrogen fertilization, fallow-season field conditions, and midseason or season-end drainage events (Pittelkow et al., 2013). In many cases, both CH_4 and N_2O are released in any drainage event, with end-of-season drainage transferring 10% of seasonal CH_4 and 27% of seasonal N_2O to the atmosphere as entrapped gases are released from the soil.

5.6 Global Context

Between 1960 and 2000, global crop net primary production (NPP) more than doubled, and global cropland area in 2011 was estimated to be 1.3 billion ha (Wolf et al., 2015). Global crop NPP in 2011 was estimated at 5.25 Pg C, of which 2.05 Pg was harvested and respired offsite (Wolf et al., 2015). Global livestock feed intake was 2.42 Pg C, of which 52% was grazed and the rest was either harvested biomass or residue collected from croplands. Global human food intake was 0.57 Pg C in 2011 (Wolf et al., 2015). The global agricultural carbon budget indicates a general increase in NPP, harvested biomass, and movement of carbon among global regions. At the global scale, cereal crops declined and have been replaced primarily with corn, soybean, and oil crops. While total NPP and yield (i.e., biomass per area) have increased in nearly all global regions since 1960, the most pronounced increase has been in southern and eastern Asia where harvested biomass has tripled. Also, cropland NPP in the former Soviet Union significantly declined in 1991, with the level of production recovering around 2010 (Wolf et al., 2015).

Annual crop cultivation and crop burning often is considered carbon neutral (IPCC 2006; U.S. EPA 2018) because biomass is harvested and regrown annually. Although biomass itself is technically carbon neutral, this assumption does not necessarily account for changes in soil carbon that may be associated with production practices, which affect the carbon cycle and net emissions. The impact of non-CO_2 emissions is accounted for in the other categories. The increased global uptake of carbon by croplands influences the annual oscillation of global atmospheric carbon (Gray et al., 2014), as more carbon is taken up and released annually than would occur without extensive global cropland production. The cycling of cropland biomass into soils and the cultivation of soils influence how much of the carbon in crop biomass is respired back to the atmosphere versus remaining in the soil, ultimately determining if a cropping system is a net source or sink.

5.7 Synthesis, Knowledge Gaps, and Outlook

5.7.1 Inventory Uncertainties

As previously discussed, enteric and manure fermentation are the sources of livestock CH_4 emissions. These two sources are affected by different factors

and carry different levels of uncertainties. The U.S. EPA estimated 95% confidence interval lower and upper uncertainty bounds for agricultural GHG emissions at –11% and +18% (CH_4 emissions from enteric fermentation) and –18% and +20% and –16% and +24% (CH_4 and N_2O emissions from manure management, respectively; U.S. EPA 2018). Whereas emissions from enteric fermentation are relatively well studied and predictable, there is larger uncertainty regarding manure CH_4 emissions and net effects of different intensities and types of grazing (see also Ch. 10: Grasslands, p. 399). Large datasets have established CH_4 emissions from enteric fermentation at 16 to19 g per kg dry matter intake for dairy cows (higher-producing cows have lower emissions per unit of feed intake) to 21 to 22 g per kg dry matter intake for beef cows on pasture (Hristov et al., 2013b). Levels of manure CH_4 emissions, however, largely depend on the type of storage facility, duration of storage, and climate (Montes et al., 2013). Emissions from certain dairy manure systems (e.g., flush systems with settling ponds and anaerobic lagoons) can be higher than estimates used by current inventories. So-called top-down approaches have suggested that livestock CH_4 emissions are considerably greater than EPA inventories. Miller et al. (2013) and Wecht et al. (2014) proposed that livestock CH_4 emissions may be in the range of 12 to 17 Tg per year, which is roughly 30% and 85% greater than EPA's estimate for 2012 (U.S. EPA 2016). Thus, future research is needed to address these discrepancies and reconcile top-down and bottom-up estimates.

Large uncertainties in GHG emissions from agricultural systems also exist because of their high spatial and temporal variability, measurement methods, cropping systems, management practices, and variations of soil and climatic conditions among regions (Hristov et al., 2017b, 2018). Uncertainty in GHG measurements often exceeds 100% (Parkin and Venterea 2010). Finally, there is considerable uncertainty in soil carbon accumulation and emissions from soils under different conditions and management practices, all of which are complicated by uncertainties about the total amount of land area under different management practices (see Ch. 12: Soils for more information on soil carbon balance).

5.7.2 Modeling and Modeling Uncertainties

Whole-farm models representing all major farm components and processes provide useful tools for integrating emission sources to predict farm-scale GHG emissions (Del Prado et al., 2013). By predicting emission processes and their interactions, models can provide a better understanding of production system emissions and be used to explore how different management decisions could affect GHG emissions. This approach has been used to estimate the carbon footprint of common U.S. dairy production systems at around 1 ± 0.1 kg CO_2e per kg fat- and protein-corrected milk produced, in which about half of these emissions come from enteric CH_4 emissions (Rotz and Thoma 2017). With a similar approach, the carbon footprint of beef cattle production was found to be 18.3 ± 1.7 kg CO_2e per kg carcass weight, with about 60% of emissions in the form of enteric and manure management CH_4 (Rotz et al., 2015).

Uncertainty exists in any measurement or projection of GHG emissions. The uncertainty of farm-scale projections is related to the uncertainty in projecting emissions from individual sources (Chianese et al., 2009). The IPCC (2006) suggested a ±20% uncertainty in predicting both enteric and manure management CH_4 emissions. Through the use of process-based models representing common management strategies for the United States, the uncertainty for predicting enteric emissions may be reduced to ±10%, but uncertainty for manure management likely will remain around ±20% (Chianese et al., 2009). Considering these uncertainties along with those of other agricultural emission sources, total GHG emissions can be determined with an uncertainty of ±10% to ±15%. As process-level models improve, verified with accurate measurements, this uncertainty can be reduced. As with inventories, uncertainties also are great for modeling agricultural carbon fluxes related to soil processes. Improving the modeling of these processes and incorporating them into large-scale carbon flux models will help increase understanding and reduce uncertainties in carbon models for agricultural lands.

SUPPORTING EVIDENCE

KEY FINDING 1

Agricultural greenhouse gas (GHG) emissions in 2015 totaled 567 teragrams (Tg) of carbon dioxide equivalent (CO_2e) in the United States and 60 Tg CO_2e in Canada, not including land-use change; for Mexico, total agricultural GHG emissions were 80 Tg CO_2e in 2014 (not including land-use change) (*high confidence*). The major agricultural non-CO_2 emission sources were nitrous oxide (N_2O) from cropped and grazed soils and enteric methane (CH_4) from livestock (*very high confidence, very likely*).

Description of evidence base

Bottom-up estimates of GHG emissions are from U.S. EPA (2018), ECCC (2017), and FAOSTAT (2017) data for the United States, Canada, and Mexico, respectively. These estimates include rice cultivation, field burning of agricultural residues, fertilization and liming, enteric fermentation, and manure management, but they do not include land-use change. The major components of agricultural non-CO_2 emissions have been consistent in numerous reports including those listed above for the emissions estimates part of this Key Finding.

Major uncertainties

Uncertainty exists in any measurement or projection of GHG emissions. Emissions from enteric fermentation are relatively well studied and predictable, but there is larger uncertainty regarding manure CH_4 and N_2O emissions. Considerable uncertainty exists in soil carbon accumulation and quantities as well as in terms of emissions from soils under different conditions and management practices. There are large uncertainties in GHG emissions from agricultural cropping systems due to high spatial and temporal variability, measurement methods, cropping systems, management practices, and variations in soil and climatic conditions among regions.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is very high certainty that N_2O and CH_4 are the major agricultural non-CO_2 emission sources. There is high confidence in the numerical estimates.

Summary sentence or paragraph that integrates the above information

For Key Finding 1, enteric CH_4 emissions are predictable, but GHG emissions from manure applications or management and agricultural soil and cropping systems are less certain.

KEY FINDING 2

Agricultural regional carbon budgets and net emissions are directly affected by human decision making. Trends in food production and agricultural management, and thus carbon budgets, can fluctuate significantly with changes in global markets, diets, consumer demand, regional policies, and incentives (*very high confidence*).

Description of evidence base

Key Finding 2 and the supporting text document the changes resulting from shifts in policy as summarized by Nelson et al. (2009).

Major uncertainties

Major uncertainties related to this Key Finding are the extent and direction of direct and indirect changes in emissions. A change in agricultural management, prompted by many possible social, economic, and policy drivers, often affects both onsite emissions (e.g., soil carbon, N_2O, and CH_4 emissions) and offsite emissions occurring upstream and downstream (e.g., in energy used for inputs to production and indirect land-use change; Nelson et al., 2009).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

The confidence that agricultural regional carbon budgets and net emissions are directly affected by human decision making is very high.

Summary sentence or paragraph that integrates the above information

For Key Finding 2, human decisions and policy very likely will affect food production and agricultural management. Management choices strongly influence emissions and soil carbon stocks.

KEY FINDING 3

Most cropland carbon stocks are in the soil, and cropland management practices can increase or decrease soil carbon stocks. Integration of practices that can increase soil carbon stocks include maintaining land cover with vegetation (especially deep-rooted perennials and cover crops), protecting the soil from erosion (using reduced or no tillage), and improving nutrient management. The magnitude and longevity of management-related carbon stock changes have strong environmental and regional differences, and they are subject to subsequent changes in management practices (*high confidence, likely*).

Description of evidence base

Most of this carbon pool exists within soils, with less than 5% residing in cropland vegetation, a finding consistent with previous reports such as the *First State of the Carbon Cycle Report* (CCSP 2007) and USDA (2016). The U.S. Department of Agriculture's Natural Resources Conservation Service has established 15 standard soil health conservation practices, which have the potential to increase soil carbon and coincidently reduce atmospheric CO_2 (Chambers et al., 2016). Evidence indicates that adoption of no tillage may increase carbon storage, especially in the soil surface, compared to conventional tillage (Chambers et al., 2016; Paustian et al., 2016; Sperow 2016), although soil heterogeneity and slow rates of change make the conclusive measurement of short-term changes difficult. It may not be appropriate to assume that adopting no tillage will sequester carbon over the long term or mitigate GHG emissions (e.g., Baker et al., 2007; Luo et al., 2010; Powlson et al., 2014; Ugarte et al., 2014). Practices that convert lands from perennial systems, such as converting retired lands or other lands to row crops, will release stored carbon back to the atmosphere (Gelfand et al., 2011; Huang et al., 2002). Conversely, management practices with the potential to release stored carbon are the inadequate return of crop residues (Blanco-Canqui and Lal 2009) and aggressive tillage (Conant et al., 2007). Conservation practices improve soil aeration, aggregate stability, and nutrient reserves, while modulating temperature and water and increasing microbial activity and diversity. As a result, soil is more resilient to climate variability and more productive (Lal 2015; Lehman et al., 2015).

Major uncertainties

Major uncertainties are related to individual practices such as no-tillage management, in particular the magnitude and longevity of changes to soil carbon stocks. Meta-analyses by Luo et al. (2010) and Ugarte et al. (2014) suggest that other factors contributing to variability in soil organic carbon sequestration include climatic and soil properties interacting with management factors (e.g., cropping frequency, crop rotation diversity, nitrogen, and drainage), along with impacts on rooting depth and above- and belowground biomass. Future shifts in management can reverse gains.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Confidence that conservation practices have the potential to increase soil carbon stocks is high.

Estimated likelihood of impact or consequence, including short description of basis of estimate

Implementation of conservation practices on croplands is likely to increase soil carbon stocks. Adopting conservation practices also provides co-benefits such as erosion control.

Summary sentence or paragraph that integrates the above information

For Key Finding 3, implementing conservation practices has strong undisputed co-benefits, including reducing erosion, and may increase soil carbon stocks over time, provided that the practices are continued. Cessation of conservation with reversion to degrading practices will result in a loss of carbon stocks and reduction of co-benefits.

KEY FINDING 4

North America's growing population can achieve benefits such as reduced GHG emissions, lowered net global warming potential, increased water and air quality, reduced CH_4 flux in flooded or relatively anoxic systems, and increased food availability by optimizing nitrogen fertilizer management to sustain crop yields and reduce nitrogen losses to air and water (*high confidence, likely*).

Description of evidence base

Agricultural soil management (i.e., synthetic nitrogen fertilizer) is a major source of GHG fluxes in North America (FAOSTAT 2017). Matching nitrogen fertilizer needs to crop needs reduces the risk of loss to air and water (Robertson and Grace 2004; Wang et al., 2011). Nitrogen fertilizer additions generally lead to increased CH_4 emissions and decreased CH_4 oxidation from soils, particularly under anoxic conditions or flooded soil systems such as rice (Liu and Greaver 2009).

Major uncertainties

Large uncertainties in GHG emissions from agricultural systems exist due to high spatial and temporal variability, measurement methods, cropping systems, management practices, and variations in soil and climatic conditions among regions (Parkin and Venterea 2010).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is high confidence that matching crop needs to nitrogen fertilizer applications can reduce fertilizer-induced GHG emissions.

Estimated likelihood of impact or consequence, including short description of basis of estimate

Avoiding excessive nitrogen fertilizer applications likely will reduce GHG emissions and provide co-benefits such as air and water quality protections.

Summary sentence or paragraph that integrates the above information

For Key Finding 4, nitrogen fertilizer is needed to support grain production. In general, there is high confidence that improving nitrogen management to avoid excess applications can reduce GHG emissions and provide co-benefits. However, considerable uncertainty still exists regarding absolute GHG fluxes.

KEY FINDING 5

Various strategies are available to mitigate livestock enteric and manure CH_4 emissions. Promising and readily applicable technologies can reduce enteric CH_4 emissions from ruminants by 20% to 30%. Other mitigation technologies can reduce manure CH_4 emissions by 30% to 50%, on average, and in some cases as much as 80%. Methane mitigation strategies have to be evaluated on a production-system scale to account for emission tradeoffs and co-benefits such as improved feed efficiency or productivity in livestock (*high confidence, likely*).

Description of evidence base

Non-CO_2 GHG mitigation strategies for livestock have been summarized in several comprehensive reviews (Montes et al., 2013; Hristov et al., 2013b; Herrero et al., 2016).

Major uncertainties

Uncertainty exists in any measurement or projection of GHG emissions. Uncertainties of GHG mitigation options are related to 1) uncertainties in projecting emissions, 2) uncertainties in projecting mitigation potential, and 3) uncertainties in the extent of the adoption of mitigation options. The uncertainty of farm-scale projections is related to the uncertainty in projecting emissions from individual sources (Chianese et al., 2009). The IPCC (2006) suggested a ±20% uncertainty in projecting both enteric and manure management CH_4 emissions. Through the use of process-based models representing common management strategies for the United States, the uncertainty for projecting enteric emissions may be reduced to ±10%, but uncertainty for manure management likely remains around ±20% (Chianese et al., 2009). Considering these uncertainties along with those of other agricultural emission sources, total GHG emissions can be determined with an uncertainty of ±10% to ±15%. As process-level models improve, verified with accurate measurements, this uncertainty can be reduced.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is high confidence that mitigation technologies can reduce livestock enteric and manure emissions. These technologies include practices related to reducing emissions from enteric fermentation (i.e., cattle) and manure management (i.e., cattle and swine) as discussed by Hristov et al. (2013b) and Herrero et al. (2016). Other potential CH_4 mitigation strategies include manure solids separation, aeration, acidification, biofiltration, composting, and anaerobic digestion (Montes et al., 2013).

Summary sentence or paragraph that integrates the above information

For Key Finding 5, effective enteric fermentation and manure emissions mitigation options are available or are expected to be available in the near future. Impact will depend on cost-effectiveness and adoption rate.

KEY FINDING 6

Projected climate change likely will increase CH_4 emissions from livestock manure management locations, but it will have a lesser impact on enteric CH_4 emissions (*high confidence*). Potential effects of climate change on agricultural soil carbon stocks are difficult to assess because they will vary according to the nature of the change, onsite ecosystem characteristics, production system, and management type (*high confidence*).

Description of evidence base

A recent analysis for the northeastern United States (Hristov et al., 2017a) estimated potential climate change effects on livestock GHG emissions.

Major uncertainties

Uncertainties include projecting climate change, its effect on animal feed intake (which determines enteric CH_4 emissions), animals' ability to adapt to climate change, and uncertainties regarding trends in animal productivity. The effect of increased temperature on manure GHG emissions is more predictable.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is high confidence that projected temperature increases are expected to decrease dry matter intake by dairy cows due to heat stress (Hristov et al., 2017a), while CH_4 emissions from manure decomposition are expected to increase (Rotz et al., 2016). Climate change effects on soil carbon sequestration balances and interactions with temperature are difficult to predict because temperature may regionally improve or degrade growing conditions, thereby shifting associated biomass inputs (Zhao et al., 2017; Tubiello et al., 2007). Likewise, increased atmospheric CO_2 will increase soil CO_2 respiration and mineralization as much as carbon inputs, resulting in little net change in soil carbon pools (Dieleman et al., 2012; Todd-Brown et al., 2014; van Groenigen et al., 2014).

Summary sentence or paragraph that integrates the above information

For Key Finding 6, projected climate changes likely will not significantly affect enteric CH_4 emissions from livestock, but increased temperature is expected to increase manure GHG emissions.

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6 Social Science Perspectives on Carbon

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KEY FINDINGS

1. *Broadened Approaches*—A range of social scientific research approaches, including people-centered analyses of energy use, governance, vulnerability, scenarios, social-ecological systems, sociotechnical transitions, social networks, and social practices, complements physical science research and informs decision making. Approaches that are people centered and multidisciplinary emphasize that carbon-relevant decisions are often not about energy, transportation, infrastructure, or agriculture, as such, but rather about style, daily living, comfort, convenience, health, and other priorities (*very high confidence*).

2. *Assumed versus Actual Choices*—Planners have assumed economically rational energy-use and consumption behaviors and thus have failed to predict actual choices, behaviors, and intervening developments, leading to large gaps between predicted rates of economically attractive purchases of technologies with lower carbon footprints and actual realized purchase rates (*high confidence*).

3. *Social Nature of Energy Use*—Opportunities to go beyond a narrow focus on the energy-efficiency industry to recognize and account for the social nature of energy use include 1) engaging in market transformation activities aimed at upstream actors and organizations in supply chains, 2) implementing efficiency codes and standards for buildings and technologies, 3) conducting research to understand how people's behaviors socially vary and place different loads on even the most efficient energy-using equipment, and 4) adding consideration of what people actually do with energy-using equipment to plans for technology and efficiency improvements (*high confidence*).

4. *Governance Systems*—Research that examines governance at multiple formal levels (international, national, state/province, cities, other communities) as well as informal processes will identify overlaps and gaps and deepen understanding of effective processes and opportunities involved in carbon management, including a focus on benefits such as health, traffic management, agricultural sustainability, and reduced inequality (*medium confidence*).

6.1 Introduction: The Social Embeddedness of Carbon

The goal of this chapter is to provide perspectives of social science research and analysis that go beyond much of available carbon science work that is sector based and economically minded—research that as yet is not sufficiently reflected in carbon cycle studies. The research discussed in this chapter thus is not intended to be a comprehensive, integrated picture of the society-carbon interaction that produces carbon emissions. Rather, the framing of the research discussed here begins with people and their social structures. This framing is different from, but complementary to, that used in the research discussed in most other chapters in the *Second State of the Carbon Cycle Report* (SOCCR2; see Box 6.1, Two Framings of Research Relevant to the Carbon Cycle, p. 266).

The framing in most of SOCCR2 begins with a description of the carbon cycle in spatial and quantitative terms, proceeds to calculations of carbon emissions to the atmosphere and their sectoral sources, and then analyzes human activities that contribute to the carbon emissions in those sectors and the impacts that increasing emissions have on physical and social systems. This framing has been used in physical science research and extended to much energy and economics research, areas not covered in this chapter.

Knowledge gained through this research framing can identify opportunities for carbon management that target the largest emissions categories (e.g., fossil fuel–based energy and transportation, urban settings, and agriculture; see Ch. 3: Energy Systems, p. 110; Ch. 4: Understanding Urban Carbon Fluxes, p. 189; and Ch. 5: Agriculture, p. 229). However,

Box 6.1 Two Framings of Research Relevant to the Carbon Cycle

Framing starting with the carbon cycle (CC):

Global CC / Fluxes → Regional CC / Fluxes → Emissions by Sector → Social "Drivers"

Framing starting with people (this chapter):

Social Structures / Processes (SS/P) → Carbon Content of SS/P → Feasible Changes

barriers to such technically oriented opportunities exist in ways of life and social or governance structures at local to global levels.

This chapter, in contrast, discusses research conducted using a framing that begins with an analysis of social conditions and structures in which carbon plays various roles. In this alternative framing, 1) the myriad and interrelated ways carbon-embedded structures and processes support ways of life become evident and 2) the socially feasible pathways to opportunities for carbon management emerge in the larger societal context. Pathways indicated under research using a people-centered framing are likely to solve multiple social goals rather than trying to achieve the single goal of emissions reductions because institutions and groups (e.g., governments, businesses, and families) have a different and broader set of issues to deal with than carbon management. Similarly, decisions that affect carbon emissions will be based on multiple factors—often including economic costs but also family, time, job, convenience, what others do, what is best for the group or organization, and other considerations.

6.1.1 Carbon Embeddedness in Social Structures and Processes

Although carbon is part of (i.e., embedded in; see Box 6.2, Embedded Carbon, this page) most social structures and processes, it is largely invisible to people as they go about their daily lives. People may (or may not) think of carbon as they see smokestacks or burn wood in a campfire because the carbon-emitting processes that produce electricity, heat buildings, and drive industrial processes may stay in the background, out of sight and out of mind.

Box 6.2 Embedded Carbon

Social science perspectives describe social arrangements and practices and then identify how carbon is embedded in them. "Embeddedness" means that carbon is an integral but often invisible part of how people lead their lives, so they do not think of themselves as using carbon but instead see the services and products without seeing their embedded carbon. Moreover, people do not often make choices about carbon as such—they choose from what is available in the market.

Nevertheless, emissions and associated structures and processes start with people—their needs and wants and how various social, political, and economic configurations and technologies both shape and are shaped by those needs and wants. From energy choices and services to economic policies and from urban hardscapes to rural landscapes, carbon is emitted, conserved, or captured as people work, travel, eat, and engage in other everyday activities and as human institutions and economic systems form and operate (see Figure 6.1, p. 267).

Research that begins by examining social structures and practices analyzes categories that may include standard sectors such as energy, transportation, buildings, and agriculture, but starting with people brings in a wide range of other topics as well. Eating, for example, a seemingly straightforward activity, encompasses a vast system of farm and

Figure 6.1. Carbon Embeddedness. As people work, learn, run errands, travel, and enjoy family and civic life, carbon is a common "thread," running through their infrastructure, tools, and environment (represented here by the white "threads" in the figure). Thus, analysis of the carbon cycle will be enhanced by identifying human uses of and reliance on carbon.

food production, agricultural policies and supports, imports and exports, transportation, middleman transactions, retail stores (e.g., location and products offered), and people's preferences along with income and health considerations. Obtaining and keeping a job, considered in a people-centered systems approach, similarly involves a range of activities such as educational opportunities and costs; income levels; locational factors such as housing, transportation, and commercial buildings (and/or home offices); access to electronic technologies; and health insurance and other benefits—the list could go on.

Social science research that examines people and the social embeddedness of carbon includes different approaches based on the research questions to be answered but often emphasizes systems and network perspectives and multiple societal factors within those systems. Because these approaches represent lines of research not assessed in the *First State of the Carbon Cycle Report* (SOCCR1; CCSP 2007), some references may predate that document.

6.1.2 Chapter Structure

First, this chapter discusses five approaches that represent lines of social science research within the climate change community, lines that are well established but usually not framed as questions about societal relationships with carbon or the carbon cycle.

- Section 6.2, p. 268. At individual, institutional, and organizational levels, behavioral research explores connections among motivation,

intention, and actors with regard to energy-related consumption and other individual and social behaviors.

- Section 6.3, p. 274. Governance research provides insights into why and how policy-environment decisions are made and implemented through both informal and formal processes.
- Section 6.4, p. 276. Scenarios of the future point to the power of connecting climate change and carbon emissions to their social-economic (socioeconomic) consequences.
- Section 6.5, p. 278. Vulnerability assessments specify who will probably be harmed by climate change, what the harm will be, and where interventions can be made at regional and local levels.
- Section 6.6, p. 279. A socioecological systems perspective demonstrates linkages among climate change–related hazards and social vulnerabilities and risks.

Next, the chapter introduces three less well known social-scientific approaches that hold potential for increasing basic understanding and providing useful future directions for decision makers to consider.

- Section 6.7, p. 280. Sociotechnical transition studies illuminate how technological transitions happen as actors, artifacts, and processes shape and reshape each other.
- Section 6.8, p. 282. Social network analyses map the connections among people with similar interests and goals, thus showing potentially changeable pathways and roadblocks.
- Section 6.9, p. 282. Social practice analyses reveal the configurations that produce emissions but also support valued, or locked-in, ways of life.

The final three sections are crosscutting. Section 6.10, p. 284, points out the crucial roles that communication and stakeholder involvement play in people-centered research. Section 6.11, pp. 285, discusses opportunities to reduce carbon emissions, including individual and social actions at various levels and timescales. Finally, Section 6.12, p. 287, provides a brief summary of findings, as well as specific steps in the path for research related to social systems and embedded carbon.

Essential to research in all these areas is increased interaction between researchers and stakeholders. Economic theory may posit people as self-interested individuals who assess a full set of information before making decisions that maximize utility at the lowest cost, but actual decision makers consider others' opinions and approval, weigh other characteristics more highly than cost, and satisfice rather than maximize (i.e., they settle for the first minimally acceptable option rather than weighing all options using multiple criteria). Understanding how people really decide and change requires questioning, observing, and interacting. According to Ch. 18: Carbon Cycle Science in Support of Decision Making, p. 728, researchers and stakeholders must co-produce knowledge.

6.2 Energy Behavior and Embedded Carbon

Although social scientists have investigated the social processes responsible for growth in carbon emissions and decline in the capacity of carbon sinks, enlarging and enriching this knowledgebase would provide better guidance for policy that addresses systems, technology design, and other efforts to reduce overall carbon emissions. In addition to energy production, expansive urban settlements, and transport systems and activities (see Ch. 3: Energy Systems, p. 110, and Ch. 4: Understanding Urban Carbon Fluxes, p. 189), researchers have considered the acquisition and accumulation of goods, as well as their embodied energy and carbon contents. Demand-side research has focused on the technical characteristics and uses of energy-powered devices, in addition to the patterns of energy demand and carbon emissions resulting from the use of buildings and appliances (Sovacool 2014). Economics work aside, the bulk of social

and behavioral sciences research and attention with respect to energy demand has been concerned with encouraging energy conservation and emissions reductions predominantly by individuals and households (Dietz et al., 2009; Stern et al., 2016; i.e., generally, behavior at the level of devices). There has been less attention to the structure and evolution of energy demand and its carbon emissions implications. For example, research on people's role in residential air conditioning has focused on how people use their air conditioning systems and how to get people to use less, rather than on the social processes involved in housing construction, device design, and lifestyles that encourage increased installation of air conditioning in buildings and vehicles.

6.2.1 What Does the Research Show?

In contrast to relating energy use and carbon emissions to devices, social science researchers have emphasized that energy use and carbon emissions are deeply interwoven—"embedded"—features of social life. Energy consumption and emissions are part of people's routines and habits, within patterns of social interaction, and are governed largely by social norms and expectations, without regard for or reference to energy sources or carbon emissions resulting from these activities. Moreover, in North America, although energy infrastructure (e.g., power lines and electrical cords) is visible, energy itself is virtually invisible to people except in special cases (e.g., cooking with a gas flame) or under unusual circumstances (e.g., appliance or system failures, grid blackouts, or energy-supply crises; Nye 2013; Rupp 2016; Shove 1997; Trentmann 2009). Although modern North American lifestyles are constrained somewhat by available energy sources and costs, they have come to represent a set of living standards and desires—normal expectations that exert growing "demands" for easily accessible energy that currently almost always is supplied across long distances and often requires considerable, yet invisible to the user, carbon emissions. Increasing installations of solar microgeneration, discussed below, could shift users' relationships with energy systems to some extent, making the sources and limitations of energy supply clearer. However, if users are to contribute to major reductions in carbon emissions, they also will modify their living standards and daily activities in the name of what they now may see as intangible environmental benefits. Thus, even if emissions were visible and easily accountable, major change would not necessarily occur, unless people see that the benefits will improve their lives in measurable ways.

As noted, both the nature of energy-using behaviors and their susceptibility to change (mostly through formal interventions) have been investigated in studies by researchers and analysts in the energy-efficiency field as well as by social scientists working in other realms. Economics has provided the most generalizable theories of investment decisions and of change (i.e., reduced consumption in response to increased unit price of energy), but the strength of relationships is often quite low (Bernstein and Griffin 2006; Kriström 2008; Lijesen 2007), related to aggregate rather than individual patterns, and compromised by what economics literature identifies as market and nonmarket failures (Jaffe and Stavins 1994).

The other, less-explicit economic explanations for energy-use behaviors and susceptibility to change given so far tend to be general and cannot be readily applied as mechanisms for reducing rates of carbon emissions, ranging from the abstract and macrohistorical (e.g., aggregate conditions and factors such as "affluence," "consumer preferences," and "institutional barriers"; NRC 2010) to the micropsychological (e.g., "motivations," "intentions," "values," "beliefs," and "propensities to adopt"; Shove 2010). These explanations often come with the assumption that actions are driven by these micropsychological properties (Ignelzi et al., 2013; Sussman et al., 2016). The descriptive layers do present ways of "seeing" people as diverse and evolving participants in energy use. Unclear, however, are how and how much the underlying qualities described in these analyses might be deliberately changed and, if they were, whether the desired reductions of energy use and carbon emissions might be achieved.

Leading-edge research has focused on diversity across individuals and households and on the layered structure of this diversity as opposed to simpler explanations rooted in isolated choices, with a particular emphasis in recent literature on populations, practices, patterns, and behavioral economics.

- Observed energy-use levels vary dramatically across populations (e.g., households or firms) due to differences in activity patterns, technical efficiency, and environmental conditions. Energy-using activity patterns are shared within groups, and different groups may have widely varying patterns of activity and modes (Lutzenhiser et al., 2017; Sonderegger 1978).

- Activities and practices, many involving energy-using equipment, emerge and are elaborated over time; some decline while others persist (Shove et al., 2012) as people modify and adapt physical systems to better meet social and cultural purposes and, in turn, modify what they do as they are "recruited" by and adopt practices (Shove et al., 2012).

- Patterns are stabilized and constrained by the characteristics of their energized technologies and infrastructure, much more so than being clusters of discrete personal behavioral choices (e.g., Shove et al., 2012).

- Insights from behavioral economics may be useful in designing instruments for energy-related behavioral change (Allcott and Mullainathan 2010) by focusing on the microstructure of decisions.

However, the complex and nuanced dynamics of energy use are not reported with much clarity in the literature. Future research could focus on understanding what influences the self-organizing nature of daily activity rather than directly engaging individuals and their behaviors.

Reviews find no overarching theory or set of consensus research methods (Lutzenhiser 1993; Wilson and Dowlatabadi 2007) and no cumulative practical understanding of "what works." Instead, there are compartmentalized disciplinary knowledgebases guided by divergent perspectives and distinct methodological preferences. In the area of applied research, narrow perspectives of program- and policy-centered research have focused on the efficacy of specific interventions or instruments, finding that certain actions may be more amenable to intervention-based change within some groups (Abrahamse et al., 2005; Ehrhardt-Martinez and Laitner 2010). Applied research on energy-conservation actions, such as equipment purchase decisions, has long been dominated by short-term policy objectives (such as responding to demand or meeting utility-savings goals) even as these goals are increasingly translated to the longer timelines of supply planning and climate change. Energy use is represented typically as averages and norms, making calculations and planning appear more tractable but generally hiding the dynamic sources, forms, and logics that create energy use.

Programs and projects that focus on or pay attention to "behavioral energy-savings potential" usually are not connected to relevant insights and framings from the social sciences or accompanied by serious considerations of how this potential might be achieved. (For a history and critique, see Wilhite et al., 2000.) These programs typically focus on discrete actions relative to assumed normative behavior—parallel to notions of technical potential via efficiency—rather than attending to how behaviors are organized (e.g., as addressed by social practice theory; see Section 6.9, p. 282). Thus, they miss opportunities provided by recognizing how systems, rather than individuals, create energy use. The findings of behavioral analysts have been used in experiments and case studies on behavioral economics (Ariely 2010; Alcott and Mullainathan 2010; Alcott and Rogers 2014), concept of "influence" (Cialdini 2010), social marketing (McKenzie-Mohr and Smith 2007), primary motivations (Pink 2010), and "nudges" (Thaler and Sunstein 2009). But that use has been without broad influence on programs and projects (Frederiks et al., 2015). Interestingly, behavioral economics experiments have found that economic incentives

and awards are weak motivators compared to, for instance, friendship ties (Ariely 2010).

Given the calls for absolute reductions in greenhouse gas (GHG) emissions rather than relative savings from energy efficiency, there is a need for a broader multidisciplinary social scientific and applied view (Keirstead 2006; Lutzenhiser et al., 2017). However, efforts to identify theoretically grounded and evidence-based "design principles" for carbon-reduction interventions are just beginning (Stern et al., 2016). Three factors hamper such efforts: 1) the absence of a systematic social science carbon-reduction research agenda, 2) the lack of adequate support from science and environmental policy agencies for social science contributions as a core component of energy-transition and carbon-mitigation research, and 3) insufficient experience in drawing together disparate scientific perspectives to address such complex high-level problems. Programs that are beginning to integrate scientific perspectives include those discussed throughout this chapter; findings from such programs are reiterated in Section 6.11, p. 285.

6.2.2 Learning from the Energy-Efficiency Experience

A good deal of the research on energy use to date has been the result of U.S. federal, state, and local policy initiatives to encourage energy efficiency (Lutzenhiser and Shove 1999). Those initiatives have recognized since the 1970s that "energy services" such as cooking, washing, heating, and cooling could be provided via technologies that, technically at least, consume much smaller amounts of energy than then-current models (e.g., Gillingham et al., 2006). Thus, public policy has focused on increasing the efficiency of appliances and buildings to displace a fraction of current consumption and delay the need for new sources of energy. Emissions reduction can be a co-benefit of energy-efficiency improvement. However, differences between efficiency improvements and reductions in absolute emissions over time are easily overlooked.

Also, because interventions to improve the energy efficiency of technologies have been funded largely by utility ratepayers under the scrutiny of public regulators, the primary focus has been on hardware upgrades and "cost-effectiveness"—not on energy users or their habits, desires, or social practices. The kinds of research needed to support these efforts have been engineering studies and economic cost-benefit analyses. Emphasis has been placed on energy cost savings.

However, behavioral science research related to interventions has shown that energy demand is not particularly price sensitive (Kriström 2008). This research has pointed to the importance of environmental values, social influences, and concerns for others as more frequent and actionable motivations for carbon-reducing equipment purchases and energy-use behaviors (Abrahamse et al., 2005; Stern et al., 2016).

Large "efficiency gaps"—gaps between predicted rates of economically attractive purchases of more efficient technology and actual realized adoption rates—have been reported regularly (Allcott and Greenstone 2012; Gillingham and Palmer 2014; Jaffee and Stavins 1994; Shove 1998). In short, energy appears to be an area where markets do not function as predicted by rational economic behavior as envisioned by classical economics—or these definitions are too simple, and there are inadequate data and understanding to represent sufficiently the complex decision processes. Programmatic explanations point to "barriers" to efficiency program participation (Golove and Eto 1996). Lists of barriers (e.g., "high discount rates" or "risk aversion") often are labels or glosses that say more about policy perspectives and program priorities than the nonadoption behaviors of actual energy users or their relationships to the energy uses targeted for change (Blumstein et al., 1980). Also, recurrent questions have been raised about "rebound effects"—the case in which expected savings from technology adoption may not be realized because of choices, behaviors, and intervening developments not predicted by efficiency-intervention planners (Gillingham et al., 2016; Herring 1999). In addition, traditional definitions of energy efficiency are

not necessarily closely aligned with issues related to carbon emissions because not only do they not take into account the carbon content of supply, they focus on relative savings rather than absolute emissions (Moezzi and Diamond 2005). More recently, scholars have stressed the importance of the "macrorebound" of carbon and energy in a growth economy (Wilhite 2016).

Many of the problems with adoption of efficient technologies can be traced to the existing situation. Regulatory logics and institutional constraints push the energy-efficiency industry, itself a socially structured enterprise, to assume that choices made by energy users are well informed and economically rational (Lutzenhiser 2014). This assumption has encouraged efforts to improve the quantity and quality of information available to energy users, with an emphasis on communicating the economic benefits of energy savings. But psychological research has shown that the "delivery" of information is far from a simple matter and that even the highest-quality information supplied as directly as possible, whether via old media or new, frequently is not acted on in the way that program developers imagine that it should, or would, be (Owens and Driffill 2008; see Section 6.10, p. 284). Even well-informed social actors routinely pass over clear and simple "rational" choices that would save money by saving energy.

This disconnect between assumptions and outcomes is as true for large firms and governmental agencies that have sophisticated information systems, analytic capacities, and strong economic interests (Biggart and Lutzenhiser 2007) as it is for individuals, households, and other groups. Explanations point to organizational structure, competing priorities and internal conflicts, risk and trust issues, and weak regulation (Stern et al., 2016). However, there also are instances of organizations leading the way in carbon reduction through corporate investment in renewable energy sources, supply-chain efficiency improvements, and energy-conscious acquisition and operation of buildings and other capital equipment (Prindle 2010; Stern et al., 2016). Research to determine how organizations variously relate to and manage carbon emissions, often in ways that defy simple explanation (e.g., by reference to cost and benefits, regulatory influence, or competition) is in its initial stages.

6.2.3 Expanding the Efficiency Policy Framework: Insights about Energy and Social Systems

Evidence suggests that various energy-efficiency technology innovations and policy initiatives undertaken over 40 years of activity in this field have saved energy (e.g., NRC 2001). However, the narrow regulatory focus and underperformance of these innovations and initiatives relative to idealized models, as discussed above, reinforce the importance of moving beyond a traditionally narrow energy-efficiency industry focus on producing energy reductions at less cost than supply (Lutzenhiser 2014). Future research and institutional changes need to recognize the social nature of energy use—including the social organization of technologies and energy systems, the social patterning of energy demands, the social nature of energy-conservation choices, and the social delivery of energy-efficiency programs and policies.

Although these social issues have rarely been explicitly considered in energy-efficiency policy or associated research, the "market transformation" strand of efficiency intervention is an important exception and success story. These activities are aimed at "upstream" actors and organizations in supply chains that engage with technology designers, manufacturers, wholesalers, and retailers to encourage, facilitate, and provide financial incentives for bringing more efficient technologies to the marketplace at appealing prices (Blumstein et al., 2000). Also, efforts by some states and the U.S. federal government to regulate the energy-using characteristics of appliances and buildings through codes and standards have had wider systemic impacts on technology efficiency. These upstream changes to improve efficiency have occurred despite strong political opposition from an array of groups and interests holding stakes in existing technologies, infrastructures, and supply arrangements (Sovacool 2008). Considerable social science research is needed on carbon management

and the market systems, supply chains, and organizational networks involved in shaping and delivering technologies (Janda and Parag 2013).

Several other strands of social research on energy use and conservation also hold promise. One has focused on the considerable variation in energy use across populations and among subgroups of energy users. Utilities and other efficiency industry actors have sometimes identified "segments" of energy users to target marketing and communications to their interests. But these efforts, redefined as the lifestyle dimension of energy—how people's behaviors socially vary and place different loads on even the most efficient energy-using equipment—offer opportunities for a better understanding of the invisible and embedded dimensions of social carbon management. In addition, periodic energy-supply crises, such as the 2001 to 2002 California electricity shortages and the 2008 loss of a substantial fraction of electricity supply to Juneau, Alaska, have provided "natural experiments" that highlight variations in energy use and in people's willingness or ability to conserve. Also shown is the malleability of taken-for-granted practices when supply is suddenly called into question (Lutzenhiser et al., 2004; Pasquier 2011) or general economic conditions worsen such as in the 2007 to 2009 recession (see Ch. 2: The North American Carbon Budget, p. 71). In addition, the past decade has seen a growing appreciation of "behavioral potentials" for energy savings (e.g., in equipment-use patterns and practices). Utility regulators and efficiency advocates have responded by adding the modification of what people actually do with energy-using equipment to the technology-efficiency improvements in their agenda.

Different strategies have been proposed to encourage those changes. A primary focus has been on mass delivery of energy usage–related information enabled by advances in electronic metering and data warehousing. The results indicate some modest aggregate reductions in overall electricity demands (Karlin et al., 2015; Power System Engineering 2010; Todd et al., 2014), even in a number of states where utility regulators only mandated delivery of information to allow persons to compare their usage to that of others (Allcott 2011; Allcott and Rogers 2014). However, these efforts have been limited in depth and aims—at least, when measured against goals—and represent small investments compared to technology-focused efficiency activities.

Despite an explicit linking of behavior changes to climate change by some academic and public-sector actors (e.g., within the Behavior Energy and Climate Change Conference, held annually since 2007 (ACEEE/BECC 2016)), the social sources and logics of energy-using practices, habits, lifestyles, and behaviors, as well as their organization and how they change continue to receive little systematic attention in U.S. scholarship. There is progress, for example, in the biannual European Summer Study on Energy Efficiency and in other efforts to "push the envelope" of energy-efficiency thinking and intervention by augmenting the classic economics framework (Frederiks et al., 2015), but this work tends to be siloed. However, there is valuable experience that can be gained from careful attention to successes and failures of energy-efficiency policy interventions, and that experience can serve as a starting point for broader and more universal carbon-reduction initiatives in the future.

6.2.4 Energy and Carbon Emissions Embedded in Complex Systems

Apart from efficiency, the other main route to reducing emissions from energy use has been developing and fostering lower-carbon energy sources. Human-centered research on this topic has focused on social acceptance of these alternatives. As much higher market shares of renewables start to become realized, researchers have started to pay closer attention to the intermittency and time-variability of renewable energy sources and how supply dynamics can synchronize with energy use rooted in temporal patterns of daily living. The social dimensions of technology acceptance (e.g., rooftop solar and wind farms, among newer technologies; nuclear power, among established technologies) and the social dynamics of routines and demand patterns (e.g., the locus of work and the cultural

definition of approved practices) will require concerted attention in social science research, carbon policy development, and energy system management. These efforts also must contend with the fact that the energetic structure of the modern North American society has developed with the experience and expectation of ready and virtually unlimited availability of energy at any time of day to fuel homes, cars, work, and play in any and all locations (see Ch. 4: Understanding Urban Carbon Fluxes, p. 189, for a discussion of urban forms).

The social-technical-environmental systems and systemic interactions involved in even the simplest energy-using and carbon-emitting human activities are complex and resistant to change via deliberate interventions—particularly on short time scales. And in that complexity, there is a "chicken and egg" quality to the relationships between supply (e.g., of goods, appliances, energy, buildings, vehicles, and transport options) and demand (i.e., for energy services). Demands are shaped and constrained by what is available, and effective supply requires that households and organizations actually consume what is offered. At the same time, suppliers attempt to encourage and increase demand through marketing, while consumers (certainly households but, most effectively, organizations) attempt to shape supply, such as through energy-related choices, regulations, and efficiency requirements. Capturing this complexity to show effective and democratic paths to reduced carbon emissions clearly requires more inclusive integrated models and increased understanding of the systems involved. This need for better models and understanding reflects earlier arguments (Douglas et al., 1998; Meadows 2008) and echoed in recent work on energy and climate change (Labanca and Bertoldi 2013; Shove et al., 2012). This also will require renewed attention to how evidence is evaluated. Next-generation analytic models and policy approaches will need to draw on new collaborations among research disciplines and between the scientific community and the social worlds in which energy is used and carbon is released to the atmosphere.

6.3 Governance and Carbon

A principal focus of climate change research comprises the kinds of governmental targets and timetables, policies, and regulations that will affect people's carbon-emitting and -capturing activities, such as energy production and land management. Social science research has expanded from an early focus on international and national governmental agreements and policies to a broader conception of carbon-relevant governance.

"Governance" refers to the processes and structures that steer society and the multiplicity of actors who are involved in this steering. The focus on governance, as opposed to governments, highlights the multiple channels through which collective interests are now pursued in the "post–strong state" era (Jordan et al., 2005; Kjaer 2004; Pierre and Peters 2000; Rhodes 1996). The complex configurations of processes and actors governing carbon emissions—who governs, with what authority, and through what means—set the context of the social, economic, and environmental costs and benefits provided by these systems (Marcotullio et al., 2014). To understand patterns of carbon emissions and, importantly, how to facilitate sustainable emissions trajectories, researchers and decision makers not only need to understand the governance processes guiding their production, maintenance, and conservation, but also need to identify feasible governance options for reducing carbon emissions.

6.3.1 Methods in Governance Research

Governance researchers use a range of quantitative and qualitative methods to understand both how particular governance arrangements arise and the social, economic, or policy consequences of different governance arrangements (Pierre and Peters 2000). Research also has focused on more normative approaches, including how governance arrangements can be designed to enhance participation and equity, be more democratic and accountable, improve efficiency, or support environmental objectives (Fainstein 2010; Hughes 2013; Pierre and Peters 2000; Sabatier et al., 2005). Increasingly, governance

research is using network-based approaches and theories to understand the complex web of actors and resources underpinning environmental planning and programs (Aylett 2013; Lubell et al., 2012; Paterson et al., 2013; Scholz and Wang 2006; see Section 6.8, p. 282, and Ch. 4: Understanding Urban Carbon Fluxes, p. 189, for a discussion of municipal networks). Governance research is often interdisciplinary, drawing on scholarship from political and policy sciences, economics, public administration, sociology, and geography (Kjaer 2004).

6.3.2 Key Findings from Governance Research

Despite previous calls for research (Canadell et al., 2010), few projects have explicitly examined the governance of the carbon cycle in North America, although there has been some work on carbon in a global context (e.g., Bumpus and Liverman 2008; Lövbrand and Stripple 2006). Rather, research tends to address carbon indirectly through analyses of governance processes and institutions operating at different scales and in different sectors related to climate change, sustainability, resilience, and even energy efficiency (Portney 2013; Wheeler 2008). Governance research increasingly has focused on the subnational level, where many North American states, provinces, and cities have taken the lead in setting ambitious GHG emissions–reduction targets and climate concerns are reshaping policy agendas across issue areas (Bulkeley and Betsill 2003, 2013; Hughes and Romero-Lankao 2014; Rabe 2004; Schreurs 2008; see Ch. 3: Energy Systems, p. 110, and Ch. 4: Understanding Urban Carbon Fluxes, p. 189, for examples of energy and urban governance). Carbon governance research also has a tendency to focus on particular sectors, such as agriculture, transportation, the built environment, and energy systems. (See Ch. 4 for a more detailed discussion of urban carbon governance.)

The work presented in other chapters indicates that energy use and production, urban areas, and agriculture are the key sectors shaping the North American carbon cycle. While scholarship typically engages with these sectors as distinctive governance realms, in reality they overlap and contradict one another in important ways. Urban form, policies, and lifestyles are responsible for more than two-thirds of global energy-related GHGs (IEA 2008), setting the demand for energy supplies and transportation behavior (see Ch. 3 and Ch. 4). Agricultural policies and priorities also shape the energy needs of this sector and, with the rise of biofuel production, can play an important role in facilitating or inhibiting renewable energy goals (Roberts and Schlenker 2013; see Ch. 5: Agriculture, p. 229). Governance research indicates that the governance systems for these three sectors differ from one another and, potentially over time, in three important ways—their sources of power and authority, institutional arrangements, and sets of their stakeholders engaged by governance processes.

Sources of power and authority can vary from more formal (e.g., U.S. federal regulations) to less formal (e.g., customer demand and preferences), and from more local (e.g., municipal governments) to more global (e.g., international agreements). Each sector engages a spectrum of power and authority sources. For example, power over land-use planning is largely local, but the forces shaping urban development patterns run the gamut from local to global (Glaeser and Kahn 2010; Salkin 2009; Stone Jr. 2009). Although U.S. federal agricultural policy plays a large role in setting incentives and policy priorities (Klyza and Sousa 2008), there is no equivalent mechanism for cities (Barnes 2005). Governance also can be driven in a more "bottom-up" fashion, as local actors and organizations seek to challenge prevailing power and authority sources that sustain existing carbon-related practices (Geels 2014; Seyfang and Smith 2007; Shove and Walker 2010).

The institutional arrangements of governance—the sets of rules, norms, and shared practices that underlie decisions—also differ among energy, urban areas, and agriculture. Institutional arrangements vary among these sectors in ways that have important consequences. Institutions may allow for greater or less public participation and engagement

from the private sector. Differences in institutional arrangements have implications for accountability of decision making and the sets of preferences and incentives shaping decision making. For example, accountability in urban governance typically lies with local elected officials—city councils and mayors—while accountability in energy production often lies with private utilities operating under widely varying mandates.

Finally, the sets of stakeholders involved in and implicated by the governance of energy, urban areas, and agricultural systems differ in terms of their priorities and position. Farmers' priorities may be entirely different from—even at odds with—those of regional energy companies or urban planners. Even within the U.S. federal bureaucracy, different agencies operate under very different sets of priorities and occupy very different positions in relation to congressional committees and regulated stakeholders; these priorities and positions may change from one presidential administration to the next. Understanding who governance stakeholders are and their priorities and positions is important for understanding carbon cycle dynamics.

6.3.3 Open Questions and Applications for Carbon Cycle Research

The differences and intersections inherent in these three sectors—agriculture, urban, and energy—mean that the path to understanding and improving governance of the carbon cycle requires knowledge of both the particularities of the different realms and the ways in which they reinforce and undermine one another. In particular, there is a need to incorporate a carbon cycle lens in research on their governance. A key area for future research will be shifting from a focus on individual policy tools (e.g., carbon pricing and energy efficiency incentives) to understanding how governance arrangements (i.e., in terms of their power structures, institutions, and stakeholder sets) shape the carbon cycle by encouraging or inhibiting energy conservation and carbon emissions reductions. Issues of fragmentation (e.g., multiple sources of partial authority) and misaligned incentives (e.g., low prices for energy supplies with large social costs) are likely to be pervasive. Another important area to examine is how emerging climate change governance arrangements (e.g., emissions trading schemes, renewable portfolio standards, urban plans, and land-management systems) interact with energy, urban, and agricultural governance systems, individually and together. Given the policy and political intersections among these realms, a focus on reducing carbon emissions may serve as an organizing force for effective carbon governance.

Despite the differences in how energy, urban areas, and agricultural systems are governed, these systems share a set of governance needs to effectively and sustainably govern carbon. All three systems require adaptability and resilience, coordination among sectors and scales, and a reorientation toward conservation and, ultimately, reducing carbon emissions (Bomberg et al., 2006; Voß and Bauknecht 2006). Research should continue to explore and identify patterns of coordinated governance among these realms and opportunities for greater coordination.

Finally, carbon governance research will benefit from more explicit attention to understanding which governance arrangements perform best according to a range of criteria.

6.4 Carbon Scenarios Embedded in the Future

Scenarios have long been used as fundamental tools to explore alternative future trajectories for the evolution of GHG emissions and atmospheric concentrations. Their development and application have spanned both quantitative and qualitative efforts to anticipate likely carbon futures, capture uncertainty in long-term carbon pathways, and establish alternative visions for the future. For example, over the past 25 years, the research community has developed and used the following as important research tools: 1) Intergovernmental Panel on Climate Change (IPCC) IS92 scenarios (IPCC 1990; Leggett et al., 1992); 2) the *IPCC Special Report on Emissions Scenarios* (SRES; IPCC 2000); and 3) most recently, Representative Concentration Pathways (RCPs; Moss et al., 2010). Such scenarios played

an important role in carbon cycle and global change research through their use as forcings for Earth System Models to estimate future changes in the physical climate system. As such, they have tended to have limited representation of the underlying socioeconomic conditions that generate the physical forcings. For example, the IS92 scenarios and RCPs are limited to concentration and atmospheric forcings of carbon dioxide (CO_2) and other GHGs. The scenarios from SRES, however, were associated with broader qualitative storylines regarding future global development, although the quantitative elements were limited to population and gross domestic product (GDP). Furthermore, the global nature of the storylines limited national, regional, or local articulation of development trajectories (Absar and Preston 2015).

In addition to their use in global change research, scenarios and scenario planning are frequently used within the private sector to explore the implications of alternative future energy, policy, and socioeconomic conditions. Shell is considered a pioneer in scenario planning for energy and climate. In 2013, Shell published *New Lens Scenarios*, which outlined technology and economic pathways to net zero carbon emissions by the end of this century (Shell 2013). More recently, Shell published *Shell Scenarios*: *Sky*, describing a pathway for delivering on the goals of the Paris Agreement (Shell 2018). Similar scenarios have been developed by other energy companies and trade associations (ConocoPhillips 2012; IPIECA 2016; BP 2018). Similarly, relevant energy and climate scenarios from national and international energy agencies include the U.S. Energy Information Agency's *Annual Energy Outlook* (EIA 2018) and the International Energy Agency's *World Energy Outlook* (IEA 2017).

Recent developments in global change research have recognized the importance of having a richer set of socioeconomic scenarios to better understand the alternative pathways by which societal development can lead to different emissions outcomes (van Ruijven et al., 2014), as well as how development can enable or constrain responses to manage risk inclusive of GHG mitigation, climate adaptation, and sustainable development. To this end, a scenario process complementary to RCPs is represented by the Shared Socioeconomic Pathways (SSPs; O'Neill et al., 2017). The SSPs consist of a set of five narratives that represent different combinations of challenges to mitigation and adaptation as well as quantitative scenarios at the national level for demography, GDP, and urbanization. Together, the RCPs and the SSPs represent the "parallel scenario process" (Moss et al., 2010), which was designed to reduce the time needed to develop scenarios for research and assessment. The RCPs enabled the climate modeling community to proceed with new simulations without waiting for bottom-up development of underlying socioeconomic conditions.

An ongoing process for the global change research community is to further elaborate and extend the SSPs to make them more useful for a broader range of social, economic, and policy research (Absar and Preston 2015; van Ruijven et al., 2014). This has included efforts to develop nested storylines for more regional analyses (Absar and Preston 2015) and to extend scenarios to address public health (Ebi 2013), as well as developing additional quantitative scenarios of other indicators (van Ruijven et al., 2014) such as poverty (Hallegatte et al., 2016). Additional effort is being invested in exploring how the SSP framework can be aligned to the Sustainable Development Goals (United Nations 2015).

A key SSP goal is to provide a flexible socioeconomic scenario framework that can be used by the global change community for diverse investigation and applications across multiple spatial and temporal scales. In particular, by integrating SSPs with RCPs, researchers can explore the development pathways that are consistent with alternative GHG concentrations, the climate implications of those concentrations, and the socioeconomic consequences of climate change, as well as mitigation, adaptation, and development policies (Kriegler et al., 2012; van Vuuren et al., 2014). In addition, opportunities exist to broaden the use of scenarios in global change research to include consideration

for normative questions such as, "What are the futures that various people want?" and "How can they be achieved?"

6.5 Vulnerability and Embedded Carbon

Because carbon is embedded in social, economic, political, and cultural arrangements, people are vulnerable to disruptions in the carbon cycle as changes in it bring changes in these social arrangements. Thus, research that first explicitly connects societal capacities, functions, and activities to carbon and then demonstrates the extent of human vulnerabilities will help to define ways to reduce those vulnerabilities. This is an alternative framing (see Section 6.1, p. 265) to vulnerability research and assessment that developed out of a framing that begins with physical changes to the carbon cycle and to climate and considers physical impacts first. (Using the physical science framing, researchers assess the vulnerability of agricultural crops and systems, species survival, future biodiversity, and ecosystem damage.)

In a framing of vulnerability assessment that investigates the potential for harm to human systems—by climate change and, by extension, the carbon cycle sources and sinks—researchers explore questions about who is likely to be harmed by climate change, how much harm is likely, compared across countries or areas, and the sources of vulnerability (exposure, sensitivity, and lack of adaptive capacity; Malone and Engle 2011). Comparative studies may aim to identify priority areas for governmental or donor investments in adaptation activities, while studies that include stakeholders may outline mitigation or adaptation activities and practices that stakeholders themselves are interested in undertaking.

6.5.1 Methods Used in Vulnerability Assessment

Researchers have used two broad approaches. The first is to select indicators of vulnerability and proxy variables (usually quantitative data) that represent those indicators and then to calculate comparative indices. The second approach is tailored to a locality by convening stakeholders and asking them to identify vulnerabilities, perhaps along with developing adaptive strategies or evaluating those already in use.

Studies have used indicators, case studies, analogies, stakeholder-driven processes, and scenario-building methodologies, sometimes employing mapping and geographic information system (GIS) techniques. These approaches often are combined to improve a given regional vulnerability assessment, and risk assessment is sometimes coupled with vulnerability assessment (Preston et al., 2009).

Stakeholder involvement has been particularly important in improving both vulnerability assessments and the design of adaptive responses (Rosentrater 2010). The community of stakeholders, whether in a village or a much larger region, then identify their community's vulnerabilities and how to address them using scenarios of the future that stakeholders develop based on relevant data, values and priorities, and realistic descriptions of what is feasible (de la Vega-Leinert and Schroter 2010; see Ch. 18: Carbon Cycle Science in Support of Decision Making, p. 728; Shaw et al., 2009; UKCIP 2001, 2005). Stakeholder involvement has been used in Canada (Carmichael et al., 2004) and the United States (NAST 2000) to build scenarios of the future.

6.5.2 Application to Carbon Cycle Research

The techniques of vulnerability assessment are well established, but the carbon cycle typically has not been part of research designs or indicators. Examples of studies that do not specify carbon cycle indicators include global vulnerability studies, in which Canada and the United States usually are ranked as having low vulnerability to climate change, whereas Mexico is ranked as having higher vulnerability (e.g., Yohe et al., 2006; Malone and Brenkert 2009). Also, subnational vulnerability studies identify economic activities and livelihoods directly related to carbon. A study of farming in Arizona (Coles and Scott 2009) showed that farmers have good access to information, notably seasonal climate forecasts, but consistently use proven short-term strategies rather

than take the large risks of changing farm animals or taking on the high cost of wind or solar energy. Furthermore, the assumption of rational decision making "ignores important influences such as tradition, identity, and other non-economic factors" (Coles and Scott 2009). Safi et al. (2012) found that rural Nevadans' risk perception of climate change is not affected by the sum of physical vulnerability, sensitivity, and adaptive capacity, but rather by "political orientations, beliefs regarding climate change and beliefs regarding the impacts of climate change" (Safi et al., 2012). For Mexico, Ibarrarán et al. (2010) assessed vulnerabilities to climate change at the state level, using comparative proxy variables; differences among the sources of vulnerability in the coming decades suggest different strategies for mitigation and adaptation. Ford et al. (2010) assessed the social factors in health-related Aboriginal vulnerability in Canada, finding that vulnerability is affected by poverty and inequality, limited technological and institutional capacity, sociopolitical beliefs, and lack of information. Furthermore, these elements of vulnerability are unevenly distributed among Aboriginal populations in Canada.

Bringing carbon considerations into vulnerability assessments has the potential to improve priorities for activities to address carbon cycle–related issues and the information base from which carbon cycle–related decisions can be made. For example, research into vulnerability that includes the carbon cycle can examine the specific implications of 1) depleted soil carbon and forest destruction in the agricultural sector; 2) the benefits of urban agriculture and methane capture for waste; and 3) the impacts of increased heat-trapping from excess CO_2 in the atmosphere (i.e., excess over what is being captured by plants, the ocean, and other sinks). This explicit inclusion of carbon can help stakeholders, who can more easily track the carbon content embedded in societal activities, as identified in vulnerability studies, than they can the more abstract long-term changes in climate. Understanding vulnerability to changes in the carbon cycle allows specific actions to reduce vulnerability by controlling emissions and capturing or conserving carbon.

6.6 Socioecological Systems and Embedded Carbon

Drawing on the seminal work of Holling (1973) to analyze complex adaptive systems and explore their resilience, researchers define socioecological systems as "nested, multilevel systems that provide essential services to society such as supply of food, fiber, energy, and drinking water" (Berkes and Folke 1998). They seek to answer research questions such as 1) What are the connections and dependencies between ecological and social systems (Berkes et al., 2003; McGinnis and Ostrom 2014)? 2) Why are some socioecological systems sustainable, or resilient, and some are not (Cole et al., 2013; Leslie et al., 2015; Ostrom 2009; Pahl-Wostl 2009)? Binder et al. (2013) describe 10 of the frameworks for conducting research on socioecological systems that include change dynamics, but the common goal is to include both social needs and the elements that create and support ecological production that, in turn, supports human beings. Interlinkages, feedbacks, and dynamics can be represented.

6.6.1 Methods Used to Analyze Socioecological Systems

Researchers who investigate socioecological systems and their resilience employ frameworks and models, often presented in network diagrams with or without multiple levels. Data may be gathered from published research, surveys, and interviews with stakeholders. Studies can be highly theoretical or focused on specific areas or systems. For instance, Cox (2014) analyzed the socioecological system of the Taos Valley Irrigation System in northern New Mexico, finding that the multilevel governance structure and the social networks have made the whole system stable and resilient. The study concludes that many factors "are needed in order to sustain complex [social-ecological systems] over time. Moreover, it is important to understand the relationships among the contributing factors. This complexity and interconnectedness would argue against the highly simplified approaches to environmental and development policy analysis that have persisted in scholarship and practice" (Cox 2014).

6.6.2 Application to Carbon Cycle Research

Applying this approach to an integrated analysis of the carbon cycle–and–human society system results in analysis of carbon as part of the configuration that supports humans with livelihoods and daily living activities. This integrated approach sets up a solution space that includes wider alternatives than those achieved simply by reducing emissions through substituting technical fixes; it can explore co-benefits (e.g., health and efficiency) that could more easily lead to action. Formulating questions such as those about people and the carbon embedded in their lives brings in considerations such as urban design, improved health, more leisure time, simplified life arrangements, and more cohesive communities.

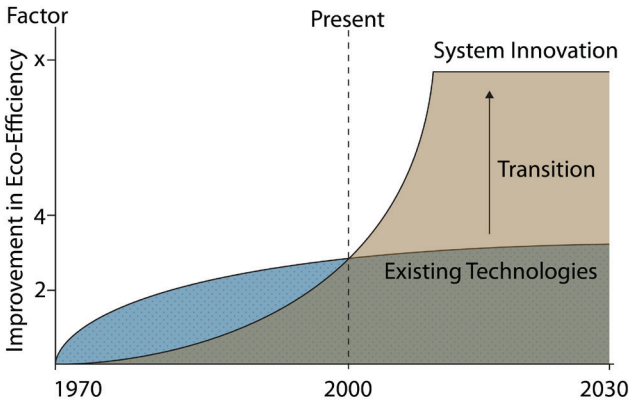

Figure 6.2. Insufficient Improvement of Existing Technologies to Meet Environmental Goals. Greater improvements in eco-efficiency can be achieved through system innovation rather than by system improvement. [Figure source: Redrawn from Vollenbroek 2002, copyright Elsevier, used with permission.]

6.7 Sociotechnical Transitions and Embedded Carbon

Reducing the anthropogenic influence on the carbon cycle implies transformative changes in sociotechnical systems. Therefore, an important issue is to understand why technological change comes about and whether or not change can be steered and accelerated.

The dynamics of sociotechnical changes and possibilities for managing them are studied in the field of sociotechnical transitions. Technologies (including those that use carbon) are deeply embedded in social practices, regulatory and market rules, landscapes, and values; the technical cannot be divorced from the social. This is a dramatic departure from traditional studies of technological change or innovation. One important assumption of sociotechnical transitions research is that greater improvements in eco-efficiency can be achieved through system innovation rather than by system improvement (see Figure 6.2, this page; Vollenbroek 2002). Systems innovation refers to alternative systems of energy, mobility, agro-food, and the closing of material loops (Geels 2002; Grin et al., 2010; Rotmans et al., 2001; Vollenbroek 2002).

Patterns of sustainability transitions are identified by Geels and Schot (2007) and de Haan and Rotmans (2011) and reviewed by Markard et al. (2012). Two foundational models for managing sociotechnical system changes are strategic niche management (Kemp et al., 1998) and transition management (Kemp 2007, 2010; Loorbach 2007; Rotmans et al., 2001). The model of transition management was developed in a project for the government of The Netherlands, based on a science-policy dialogue, details of which are described in Kemp and Rotmans (2009) and further developed by Loorbach (2007).

Transition management seeks to create system innovations through a model of guided evolution. Acting as a process manager, government mobilizes the interests of industry and society in system change with sustainability benefits (Kemp et al., 2007). Transition management methodology comprises the following elements (Meadowcroft 2009):

- Making the future more clearly manifest in current decisions by adopting longer time frames, exploring alternative trajectories, and opening avenues for system innovation, as well as system improvement;
- Transforming established practices in critical societal subsystems within which unsustainable practices are deeply embedded;

- Developing interactive processes where networks of actors implicated in a particular production-and-consumption nexus can come together, develop shared problem definitions, appreciate differing perspectives, and above all develop practical activities;
- Linking technological and social innovation because both sorts of change are necessary if society is to move to a more sustainable pathway;
- "Learning-by-doing," developing experiments with novel practices and technologies because only by initiating change can societies learn the potential, and the limits, of different approaches;
- Tailoring support for technologies to different phases of the innovation cycle;
- Encouraging a diversity of innovations (i.e., variation) and competition among different approaches (i.e., selection) to fulfill societal needs; and
- Assigning an active role to government in mobilizing society to orient change in desired directions.

The visions for the future and details of policy are determined by political leaders, legislative bodies, and voter preferences, not by special agencies. The commitment to long-term change helps to orient state politics more toward system innovation. Government thus responds to calls for change from people and organizations by nurturing new technologies and, once these are better developed, supporting them more actively through diffusion policies. The availability of well-developed alternatives will give policymakers an easier path to introduce policy instruments such as carbon taxes and to phase out carbon-based technologies.

Analytically, the sociotechnical transition perspective examines interaction effects (i.e., coupled dynamics) among actors, technologies, rules, and institutions in evolving landscapes, as the broader context of sociotechnical regimes and niches of radical change. Such interactions give rise to four distinct transition patterns: substitution, transformation, reconfiguration, and de-alignment and re-alignment (Geels and Schot 2007). Specific pathways depend on structural landscape factors that shape action possibilities. Such factors include the presence of a strong and well-organized civil society with active cooperatives, citizen groups, activities, and socially engaged scientists; the salience of environmental issues in politics; and the industrial base for producing eco-innovations—all factors that were stronger in Germany than in the United Kingdom (Geels et al., 2016). In transition processes, no one is in control, and the interaction among different developments gives rise to outcomes that enhance the position of certain actors and technologies. New circumstances and counter strategies from incumbents, however, may change the trajectory.

The sociotechnical perspective emphasizes 1) the centrality of actors, while also being mindful of material aspects (e.g., in the forms of material interests, technologies, and infrastructures), 2) hybrid systems (e.g., decentralized technologies integrated into centralized systems), 3) spillovers from sectoral developments and various policy agendas, and 4) the duality of agency and structure. Attention to niche actors and landscape factors helps researchers to understand the demise of sociotechnical regimes such as in a substitution pathway and their gradual transformation in the three other pathways.

Under transition management approaches, societal interests in alternative technologies and system change are exploited in ways that fit with local circumstances. Transition thinking helps policymakers and actors in society to undertake useful actions in the forms of transition experiments, creation of transition platforms, and use of monitoring systems for managing the energy transition and the transition to the circular economy. These activities complement policies such as carbon taxes, regulations and soft obligations that constitute the Paris Agreement approach (Rajamani 2016), and national sustainable energy policies.

Laws and the embedding of transition endeavors in institutional frameworks help in pursuing transitions but are no guarantee of success. Research indicates that sustainability transitions require both control policies, pursued with rigor and perseverance, and innovation-support policies (Ashford and Hall 2011). Transition endeavors are likely to encounter opposition from incumbent actors, which can be observed in every transition process.

6.8 Carbon Connections in Social Networks

Social network analysis maps the connections among people who have links to one another. The focus is on the nature and strength of the links instead of on any characteristics of the individual members of the network. Examples of links relevant to the research include 1) "gives information to/receives information from," 2) "has a similar worldview," 3) "shares resources with," or 4) "is a coauthor of." Mapping the social network can provide insights about leadership and power structures.

6.8.1 Methods Used in Social Network Analysis

Social network analysis starts with a matrix drawn usually from a survey that shows the links among members of a defined social network. Software is used to both determine and display the linkages found, often with their strength, and to measure such characteristics as important nodes (i.e., centrality), density (i.e., out of the possible links, what is the proportion that actually exists?), and the length of certain pathways (e.g., through how many nodes must information go to get from one person to another?).

6.8.2 Applications to Carbon Cycle Research

Current relevant work, with few exceptions, does not focus on carbon but rather on climate change and disasters. Broadbent studies policy networks in the Comparing Climate Change Policy Networks project known as COMPON (see Broadbent and Vaughter 2014), which has teams in the United States, Canada, and Mexico (among other countries). Armitage et al. (2011) used social network analysis in case studies of co-management institutions for Canadian Arctic fisheries, finding that, over time, these networks co-produce knowledge, drawing on scientific and indigenous sources, that enables learning and adaptation. Malone (2009) used social network analysis to find shared elements of arguments (e.g., worldview, types of data used, authorities used, and solutions proposed) in the climate change debate, finding multiple connections even among analysts who make different arguments. Researchers also have studied disaster-response networks (Kinnear et al., 2013; Robins et al., 2011), where trust is a significant element in coordinated activity. Concerns about carbon link researchers and decision makers in complex networks, but these networks have not been mapped.

6.9 Social Practices and Carbon Configurations

The social practices perspective (Shove et al., 2012) offers a potentially useful approach to the needed "integrated models" discussed in Section 6.2, p. 268. As noted, the focus of U.S. demand-side energy policy has been on improving the efficiencies of devices, with limited attention to energy users, their energy uses, or the social shaping of energy consumption (Lutzenhiser 2014). Similarly, Mexico's Energy Reform program has targeted the technical aspects of equipment, appliances, and energy consumption in public buildings, rather than a more systematic view that starts with a framing of meeting people's needs for energy in low-carbon ways (Valdez 2015).

The social practices perspective takes a more explicit social sciences–based approach to understanding energy use and carbon emissions, offering new ways of seeing complexity and understanding the possibilities for change in social patterns of consumption. Rather than focusing on technologies, behaviors, and desires, for example, as relatively independent, this perspective takes "practices" as the object of inquiry, highlighting how daily living rests on dependencies among people, activities, technologies, and supply

systems, as well as how the various practices relate to each other. It thus involves appreciating the social origins of taken-for-granted "needs" for particular goods and services, which, in reality, vary considerably across time, space, and populations. By not assuming that patterns of activity—human interactions with technologies or current levels of energy use—are fixed or unquestionable, the practices perspective can lead to rethinking housing, transportation, home-workplace relationships, lifestyles, technology designs, and policy approaches.

Social practice theory applied to energy use and carbon emissions draws on several overlapping strands of contemporary research. One strand is sociological theory concerned with how social structures come into being and are reproduced at multiple scales—from the individual to the group, social institutions, and macro-organization within and between societies in the global system (e.g., Giddens 1984). A second is an appreciation that social actors' household habits and routines involve ongoing skilled cultural interactions with technological artifacts and sociotechnical systems (Lutzenhiser 1992). The third recognizes that actors' and households' understandings of their own energy-using activities are important to grasp as they are expressions of larger institutional beliefs and knowledge systems (Shove et al., 1998). Together, the strands focus attention on the systematic interactions among human actors, devices, meanings, skills, infrastructures, and social systems—compared to the more traditional focus on elements in relative isolation (e.g., behaviors, needs, and appliances) that was common in earlier research on energy use and energy efficiency.

Examples of social practices include cooking and eating, driving, walking, riding, using personal and family electronic devices, heating and cooling, washing, entertaining and visiting, and home buying and renovating. While their expression can vary considerably within societies, by definition social practices are not idiosyncratic; they are shared and maintained by social groups. Practices are patterned and clustered with other practices. They often are taken for granted but can become problematic and subject to criticism (e.g., use of water on lawns in drought areas, driving cars short distances for errands, and wearing business suits in the summer in Japan). Practices have histories; they change over time, and they are bundled with physical materials and technologies in mutually supportive relationships. They are sometimes discarded but also can persist long after the conditions that gave rise to them have changed; discarded practices also can be subsequently revived and adapted. In this view, all carbon emissions are produced as a by-product of social practices—and social practices are produced within a complex of social circumstances, rather than by isolated free will.

The importance of beginning research by analyzing these practices to assess the "social potential" (Shove et al., 2012) of interventions in the carbon cycle follows from the fact that, while most energy use and carbon emissions themselves are invisible to the people and groups responsible for them, they are embedded in immediately meaningful social patterns and norms. Therefore, practices often are locked in by shared habits and expectations that require the use of particular devices (e.g., appliances, automobiles, and office buildings) that, in turn, depend on the energy flows and emissions of the larger sociotechnical systems to which they are connected. And these larger systems prove to be incredibly complex, made up of linked technologies and infrastructures, codes and regulations, organizational structures and networks, geographies, and shared scientific and technical knowledge frameworks (Bijker et al., 1987).

Thus, the social practice theory view appreciates this complexity and concludes that what people do with their lives—how they live and relate to others—has considerable salience and importance for carbon emissions reduction, and largely abstract calls for change should be met with skepticism. As a general rule, changes in practices should be expected to be hard to achieve as a policy or market goal, and the hoped-for "levers" of change in practices may well demand coordinated action on interconnected elements of social, technical, political, cultural, environmental, and economic systems. Nonetheless, changes

in practices are continually occurring, sometimes in directions that seem "desired" from the perspective of climate change goals and policies. Funding from European scientific and energy agencies is being directed toward understanding the evolving carbon-emitting practices of households and organizations, with attention to origins, dynamics, interdependencies, and trends—including the effects of innovations in technology and policy on changes in social practice (DEMAND 2016; RCUK 2016).

6.10 The Roles of Communication and Stakeholder Involvement

Although people generally respect science and scientific findings, the so-called science-policy gap persists. The gap appears when scientific findings that seem to call for policy action are not taken up by policymakers in expected ways. Thus, renewed attention has been focused on how to communicate scientific findings to facilitate their enaction. Communicating scientific findings can be ineffective depending on the subject matter, the framing used, and the ways in which messages are delivered. What people choose to believe is heavily influenced by their political environment (Lupia 2013) and by religious or political beliefs (Nisbet and Scheufele 2009). For example, if science reaches consensus on a new rocket technology, there is little question from the public about its legitimacy. On the other hand, if observations and analyses are contrary to political messaging or bring into question belief systems, scientific information can be quickly discounted. Research has been conducted to understand this phenomenon in an effort to identify core issues and a path forward for effectively communicating science.

Initial indications are that cultural and peer-group dynamics are more influential than science literacy and the communication of scientific evidence (Kahan et al., 2012). A follow-up study used a different set of questions to rate "open-mindedness" of individuals and found that the metric only reinforces and accentuates existing beliefs (Kahan and Corbin 2016). Similarly, a comprehensive review of 171 studies from 56 nations found that acceptance of climate change science is more strongly predicted by cultural variables such as ideology and political orientation than by demographic variables including age, gender, income, and ethnicity (Hornsey et al., 2016). More research is needed to understand how individuals assimilate knowledge, particularly if it runs contrary to cultural or peer-group influences. Results from this research might be useful in guiding alternative ways to communicate carbon cycle science results more effectively.

Based on the more recent findings of science knowledge assimilation, frameworks for science communication continue to evolve. New models of science communication have been proposed that would require a coordinated effort to identify questions, conduct research to address the questions, and understand how to best communicate the answers in a robust and supported manner (Pidgeon and Fischhoff 2011). A contemporary definition of science communication outlines specific components that should be addressed when communicating science (Burns et al., 2003). A renewed look at how communication is occurring over social media and how science communication can adapt to the new media landscape has been suggested (Brossard and Scheufele 2013).

Research indicates that communicating consensus around science topics increases public acceptance of the findings, but that a process known as attitudinal inoculation may be needed to maintain acceptance (van der Linden et al., 2017). This process essentially consists of pre-emptively highlighting and refuting false claims and potential counterarguments, such as those made by climate change deniers (Oreskes and Conway 2011). False claims and intentional dissemination of misinformation on related science topics have been analyzed by the research community (Farrell 2016; Supran and Oreskes (2017). A concentrated focus on methods of science communication, based on current understanding of knowledge assimilation, will be critical to enabling the use of science for decision making. Likewise, renewed efforts on making science results more accessible and relevant to collective decision

making, using current communication technologies, are needed.

Many of these research studies examine one-way communication: from scientists to audiences including policymakers, business people, and the general public. Another form of communication, stakeholder involvement—a standard social scientific method—helps researchers and decision makers to address issues and agree on actions (O'Connor et al., 2000; Fiack and Kamieniecki 2017). Mutual exchanges among stakeholders (policymakers and others involved in carbon-relevant decisions) bring to light people's values, concerns, and sticking points and allow dialogue needed to establish feasible options and implement programs. Stakeholder involvement typically identifies co-benefits of reducing emissions; multiple benefits help to gain widespread acceptance. Examples include changes that bring benefits such as reduced air pollution with associated health benefits or new jobs in renewable-energy industries. Other benefits could include amenity improvements from increased urban tree cover, more efficient heating and cooling systems, the convenience of "walkable" neighborhoods, and the safety of buildings that can withstand high winds and flooding.

What may emerge in stakeholder-science-policy dialogues are gradually increasing levels of agreement on issues as well as a variety of options for action. People in direct communication may discover that they are arguing from different viewpoints; missing practical concerns or obstacles; and/or that they actually agree within a mutually defined framing of problems, solutions, or both (Hulme 2009; Malone 2009).

Stakeholder involvement and associated communication exchanges between scientists and decision makers improve the likelihood that pathways forward can be identified, adopted changes will be implemented, and that further changes will be adopted over time.

6.11 Opportunities to Reduce Carbon Emissions

Because changes in social, institutional, and technological structures and practices result from people's decisions to change, the opportunities to reduce carbon emissions are broad-ranging. This section will focus on opportunities for behavioral and institutional changes as described in the research literature.

The IPCC (Blanco et al., 2014) summarized the state of social and behavioral sciences research:

"There are many empirical studies based on experiments showing behavioural interventions to be effective as an instrument in emission reductions, but not much is known about the feasibility of scaling up experiments to the macro economy level. … The net effect of trade, behaviour, and technological change as a determinant of a global increase or decrease of emissions is not established." (Blanco et al., 2014)

Obvious pathways to explore in efforts to reduce carbon emissions are to change individual and group behaviors—for instance, to dial down thermostats, drive and fly less, buy energy-efficient appliances, eat less meat, and plant trees. Dietz et al. (2009) estimated the behavioral potential of these kinds of changes. They found that "the national reasonably achievable emissions reduction (RAER) can be about 20% in the household sector within 10 years if the most effective nonregulatory interventions are used. This amounts to 123 metric tons of carbon (Mt C) per year, or 7.4% of total national emissions" (Dietz et al., 2009). Actions included home weatherization, upgrades of heating and cooling equipment, more efficient vehicles and home equipment, equipment maintenance and adjustments, and daily use behaviors.

Stern et al. (2016) point out that interventions must "take into account key psychological, social, cultural and organizational factors that influence energy choices, along with factors of an infrastructural, technical and economic nature. Broader engagement of social and behavioral science is needed to identify promising opportunities for reducing fossil fuel consumption" (Stern et al., 2016). These researchers then describe short-term, intermediate, and long-term changes that could reduce fossil fuel consumption (FFC). Table 6.1, p. 286, is adapted from a portion of their table that listed actions for

Table 6.1 Changes to Reduce Fossil Fuel Consumption at Various Social and Temporal Scales[a,b]

Social Scales and Roles	Temporal Scales		
	Short-Term Actions (Moments to Days)	Intermediate Actions (Weeks to Decades)	Long-Term Actions (Generational, Transformational)
Organizations as energy consumers	Induce employees to reduce energy use (e.g., in offices, minimize use of task lights, computers, auxiliary heating and cooling devices). Reduce motorized business travel (e.g., by using video conferencing). Assign staff "energy champion" responsibilities. Manage production systems in response to real-time price signals.	Make reducing fossil fuel consumption (FFC) a strategic part of core business operations. Replace lighting and HVAC systems, equipment, and motor vehicles with energy-efficient models. Rent or procure low-FFC buildings when relocating. Adopt photovoltaic systems. Change work styles to accommodate a broader range of thermal conditions (e.g., Japan's Super Cool Biz program).	Change core business offerings to align with climate challenges (e.g., BP's short-lived "beyond petroleum" experiment, or Interface Carpet's goal of carbon neutrality).
Organizations as providers of goods and services	Find lower-footprint supply sources. Inform customers on how to use products and services offered in an energy-efficient way. Reduce FFC in the production chain.	Make reducing FFC a strategic part of core business offerings. Support and train staff in systems thinking and sustainability. Redesign products for lower energy requirements. Elect to manufacture, market, and service low-FFC products.	Develop lower-carbon, industry-wide standards (e.g., carbon labeling schemes for suppliers).
Large-scale social systems	Improve crisis responses to power outages and fuel shortages.	Adopt policies to encourage and assist lower-FFC actions in households and organizations. Create institutions and norms for lower-FFC actions in groups of organizations.	Improve public transport system. Design communities for easier nonmotorized travel. Change norms for socially desirable housing, vehicle types, workstyles, and work practices.

a) Adapted from Stern et al., 2016.

b) Key: FFC, fossil fuel consumption; HVAC, heating, ventilation, and air conditioning.

organizations (i.e., consumers and producers) and large-scale social systems.

6.12 Conclusions

6.12.1 Research Insights

Findings from these lines of research draw on scientific knowledge about social change, the role of science in societies, multilevel governance, and social-psychological behavior in many settings. The following research findings and insights reflect the people-centered framing discussed throughout the chapter and hold promise for future exploration.

People-Centered Research. Research that is framed to begin with people and explore how various social, political, and economic configurations and technologies have carbon embedded in them reveal points of intervention that are practical and feasible.

Expanded Use of Data. "Big data" and associated data-mining activities related to social segments, lifestyles, and purchasing and activity patterns could significantly expand relevant knowledge about people, social systems, and embedded carbon.

Analysis of Real-Life Decision Making. Understanding how people really decide and change requires questioning, observing, and interacting; decision makers rarely make ideal, completely rational decisions.

Invisibility of Energy and Emissions. Energy consumption and emissions are part of people's routines and habits, within patterns of social interaction, and are governed largely by social norms and expectations—without regard for or reference to (out-of-sight) energy sources or carbon emissions resulting from these activities.

Shared—and Varied—Patterns of Energy Use. Energy-using activity patterns are shared within groups, stabilized and constrained by energized technologies and infrastructure; large variations are seen in different groups, across populations (e.g., of households or firms), and over time as people modify and adapt.

Relative Unimportance of Cost Motivations. Environmental values, social influences, and concerns for others are more frequent and actionable motivations for carbon-reducing equipment purchases and energy-use behaviors than are potential cost savings.

Deeper Understanding of Consumer Behavior. Although the energy-efficiency industry tends to assume that customers are rational in evaluating information, psychological research has shown that even well-informed social actors routinely pass over clear and simple "rational" choices that would save money by saving energy.

Success in Marketing Efficient Technologies. "Market transformation" research has been successful in identifying "upstream" actors and organizations in supply chains and engaging with technology designers, manufacturers, wholesalers, and retailers to encourage and facilitate bringing more efficient technologies to the marketplace at appealing prices.

Codes and Standards for Efficient Technologies. Efforts by some states and the U.S. federal government to regulate the energy-using characteristics of appliances and buildings through codes and standards have had wide systemic impacts on technology efficiency.

Importance of Considering User Behavior. "Behavioral potentials" for energy savings (e.g., in equipment-use patterns and practices) have become increasingly recognized. When planning efficiency improvements, utility regulators and efficiency advocates have added the consideration of what people actually do with energy-using equipment to the technology specifications.

Understanding and Modeling Complex Decisions. Capturing the complexity of carbon-relevant decisions to show effective and democratic paths to reduced carbon emissions could be accomplished through developing inclusive integrated models and increased understanding of the systems involved.

Improved Understanding of Governance Processes. To understand patterns of carbon emissions and, importantly, how to facilitate sustainable emissions trajectories, researchers and decision makers would benefit from increased understanding of the governance processes guiding emissions' production, maintenance, and conservation, leading to identification of feasible governance options for reducing carbon emissions.

Differences and Common Needs Among Governance Systems. The governance systems for the energy, urban, and agricultural sectors overlap and sometimes contradict one another; they differ from one another in three important ways: their sources of power and authority, their institutional arrangements, and the sets of their stakeholders engaged by governance processes. Despite the differences in how these systems are governed, they share a set of governance needs to effectively and sustainably govern carbon—needs to adapt, increase resilience, coordinate among sectors and scales, and reorient toward conservation and, ultimately, reducing GHG emissions.

Broadened Use of Scenarios. Opportunities exist to broaden the use of scenarios in global change research to include consideration for normative questions such as, "What are the futures that various people want?" and "How can they be achieved?"

Systems Analysis to Improve Options for Effective Action. Analysis of carbon as part of a socioecological system that supports humans with livelihoods and daily living activities sets up a solution space that includes wider alternatives than simply reducing emissions by substituting technical fixes; the socioecological approach can explore co-benefits (e.g., health and efficiency) that could more easily lead to action.

Technologies as Embedded in Social Systems. Technologies are deeply embedded in social practices, regulatory and market rules, landscapes, and values; the technical cannot be divorced from the social.

Needs for Both Policies and Markets. Well-developed systems are unlikely to be overthrown by new ones through market processes: sustainability transitions likely will be faster and more comprehensive with strong governmental policies in the form of a phase-out of unsustainable technologies. Research indicates that sustainability transitions benefit from control policies, pursued with rigor and perseverance, next to innovation-support policies.

Analysis of Social Practices. Daily living rests on dependencies among people, activities, technologies, and supply systems and how various social practices relate to each other. It thus involves appreciating the social origins of taken-for-granted "needs" for particular goods and services, which, in reality, vary considerably across time, space, and populations. By not assuming that patterns of activity—human interactions with technologies or current levels of energy use—are fixed or unquestionable, the practices perspective can lead to rethinking housing, transportation, home-workplace relationships, lifestyles, technology designs, and policy approaches.

Two-Way Communication. One-way communication of scientific findings is problematic (especially when people's values or beliefs seem threatened), but well-designed stakeholder involvement can result in mutually accepted actions.

6.12.2 Research Priorities

Carbon is embedded in myriad types of social-economic-political-cultural institutions and thus is involved in the interwoven systems that emit and sequester carbon. Human institutions include government, industry, energy, transportation, buildings, urban areas, land, agriculture, and households. The current state of the carbon cycle is, therefore, an extremely complex, although not intractable problem. Recognizing the social embeddedness of carbon leads to research that will deepen knowledge about how social systems both persist and change, indicating pathways by which carbon emissions can be reduced and carbon sequestration increased.

Although much valuable research is sector based and economically minded, social science researchers have gone beyond these types of research to develop approaches that focus on people and their social configurations—systems of systems—that have carbon embedded in them. This focus is important to assess uncertainties and the progress of mitigation and adaptation efforts. More and more, the challenge of carbon cycle research and management is to deepen basic understanding of how people are negotiating change in their own interests as they live and participate within organizations and institutions, according to constraints, opportunities, and values in specific situations. If people are to contribute to major reductions in carbon emissions, they also will modify their lifestyle choices in the name of what they may initially perceive as intangible or yet-unknown environmental benefits.

The research lines described in this chapter lend themselves both to interdisciplinary research and to stakeholder involvement in development of research questions, priorities of decision makers, and feasibility of proposed actions. Future research needs encompass a spectrum of approaches, as listed below, to increase understanding of people's decision making and change processes.

Theory and Data Gaps. Opportunities to better leverage existing social science datasets or approaches for climate and carbon research include the following:

- *Theory without data.* Potentially useful social science theories—including social survey–based analysis; ethnographic analysis; and narrative sources of insight into people's beliefs, understandings, and actions—have been applied only limitedly to climate change research.
- *Granular data on human activities currently applied almost exclusively for commerce.* In particular, big data and associated data-mining activities related to social segments, lifestyles, and purchasing and activity patterns could significantly expand relevant knowledge about people, social systems, and carbon. However, this potential has not yet been deployed or customized for climate change questions.
- *Data with little or no theory attached.* They include highly aggregated census data and utility billing data, which are common in policy analyses but lack information about users. Social sciences have had only limited involvement in such analyses.
- *Data analysis methods and the evaluation of scientific acceptability.* These approaches are not yet advanced enough to sync with the new worlds of data and types of issues to be addressed.

Recognition of the Social Nature of Energy Use. Future research and institutional changes would benefit from recognizing the social nature of energy use—including the social organization of technologies and energy systems, the social patterning of energy demands, the social nature of energy-conservation choices, and the social delivery of energy-efficiency programs and policies.

Broader Views of Governance. A key area for future research will be shifting from a focus on individual policy tools (e.g., carbon pricing or energy-efficiency incentives) to understanding how governance arrangements (in terms of their power structures, institutions, and stakeholder sets) shape the carbon cycle by encouraging or inhibiting energy conservation and reducing carbon emissions. Issues of fragmentation (e.g., multiple sources of partial authority) and misaligned incentives (e.g., low prices for energy supplies with large social costs) are likely to be pervasive.

Links Among Carbon Management and Other Governance Arrangements. Emerging climate change governance arrangements (e.g., emissions trading schemes, renewable portfolio standards, urban plans, and land-management systems) will interact with energy, urban, and agricultural governance systems, individually and together. Integrated research will represent these interactions.

Technological Transitions. Social scientific research provides better understanding of why transformative technological change comes about and whether or not change can be steered and accelerated in sociotechnical systems to lessen the anthropogenic influence on the carbon cycle.

Social Networks and Practices. Research can map social networks of relevant potential actors in carbon cycle research and mitigation activities and describe everyday practices in which carbon is embedded; both approaches can reveal potential pathways for carbon management.

Use of Existing Tools and Methods. Research that applies such developed methods as scenarios, vulnerability assessment, sociological systems, social network analysis, and social practices analysis to include the carbon cycle will highly complement physical science research by providing understanding of social perceptions of and engagement with aspects of the carbon cycle.

SUPPORTING EVIDENCE

Process for Developing Chapter

This chapter was developed as part of the overall process for initiating the *Second State of the Carbon Cycle Report* (SOCCR2). Although "societal drivers" were specified as a section in all chapters, the Federal Liaisons and Science Leads agreed that a separate chapter on relevant social science research was needed to strengthen the report and respond to the recommendations of the *First State of the Carbon Cycle Report* (SOCCR1). The chapter contents were developed through conference calls and discussions with comments from scientists, U.S. federal agency personnel, and the public.

KEY FINDING 1

Broadened Approaches—A range of social scientific research approaches, including people-centered analyses of energy use, governance, vulnerability, scenarios, social-ecological systems, sociotechnical transitions, social networks, and social practices, complements physical science research and informs decision making. Approaches that are people centered and multidisciplinary emphasize that carbon-relevant decisions are often not about energy, transportation, infrastructure, or agriculture, as such, but rather about style, daily living, comfort, convenience, health, and other priorities *(very high confidence)*.

Description of evidence base

For Key Finding 1, physical scientific research has produced extensive information on the so-called greenhouse effect, the overall warming of the global climate, and the contribution made to climate change by human-caused emissions of heat-trapping gases; studies of the carbon cycle have confirmed that carbon is being emitted to the atmosphere from human activities. Research that starts with this framing has quantified sectors and activities where mitigation of climate change is technically possible. Yet the ideal global policies, national commitments, and implementation of such policies have not taken place to the degree necessary to substantially reduce emissions. Relevant social science research is needed to understand feasible pathways to both mitigation and adaptation actions using a framing that is centered on people. This need has been increasingly recognized by the Intergovernmental Panel on Climate Change (IPPC) and other international, regional, and local organizations concerned with climate change. See Section 6.1, p. 265; Section 6.2, p. 268; and Section 6.11, p. 285, for a more detailed description of the evidence base and relevant citations.

Major uncertainties

Uncertainties include the degree to which societies are vulnerable to climate change, the systematic implications of various candidate actions and policies in specific places, and the capacity and willingness of human institutions and individuals to act.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Evidence from the existing body of social scientific research has identified feasible pathways to mitigation with very high confidence.

Summary sentence or paragraph that integrates the above information

There is very high confidence in Key Finding 1 that people-centered social science research can explore and demonstrate feasible and implementable mitigation strategies and actions.

KEY FINDING 2

Assumed versus Actual Choices—Planners have assumed economically rational energy-use and consumption behaviors and thus have failed to predict actual choices, behaviors, and intervening developments, leading to large gaps between predicted rates of economically attractive purchases of technologies with lower carbon footprints and actual realized purchase rates *(high confidence)*.

Description of evidence base

From large potential emissions reductions calculated by integrated assessment models to expected behavior changes encouraged by employers, results of first-best policies and programs have been disappointing at levels from the global to the local. See Section 6.2.2, p. 271, for a more detailed description of the evidence base and relevant citations. Even activities such as methane capture, which has been calculated to be economically profitable, have not been widely implemented by mining and other industries. Lifecycle calculations that show savings from energy-efficient technologies such as weatherstripping, insulation, and heating and cooling equipment have failed to prompt rational choices to increase energy efficiency or purchase energy-efficient homes in numbers near the technical potential. See Section 6.2.2, p. 271, and Section 6.9, p. 282, for a more detailed description of the evidence base showing the difference between predicted, economically rational decisions and actual decision-making processes.

Major uncertainties

Although much has been learned about such "market failures" or "barriers," the reasons for gaps between predicted and actual results encompass factors that are still uncertain in their specific roles and magnitudes.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Numerous studies have conclusively documented gaps between predicted or potential emissions reductions and actual choices and behaviors, leading to a very high confidence level.

Summary sentence or paragraph that integrates the above information

Science findings for Key Finding 2 demonstrate a very high confidence that planners should not assume rational behavior of people and organizations in acquiring more efficient technologies and using them efficiently

KEY FINDING 3

Social Nature of Energy Use—Opportunities to go beyond a narrow focus on the energy-efficiency industry to recognize and account for the social nature of energy use include 1) engaging in market transformation activities aimed at upstream actors and organizations in supply chains, 2) implementing efficiency codes and standards for buildings and technologies, 3) conducting research to understand how people's behaviors socially vary and place different loads on even the most efficient energy-using equipment, and 4) adding consideration of what people actually do with energy-using equipment to plans for technology and efficiency improvements *(high confidence)*.

Description of evidence base

Key Finding 3's four specific areas reflect current research that shows promising results from people-based approaches. Focusing on the systems involved in supply chains—technology

designers, manufacturers, wholesalers, and retailers—brings people and organizations together in a common purpose to facilitate and provide financial incentives to bring more efficient and less carbon intensive technologies and processes into an industry. Similarly, codes and standards for buildings and technologies create industry-wide benchmarks and so encourage sharing of knowledge and practices as well as competition to be efficient or meet a standard such as "Energy Star" (www.energystar.gov). The variations in human energy use by place and social condition have been well established, but people-based research showing why such variations exist and how they can be addressed needs to be expanded and strengthened. When planners include studies of actual energy-use requirements instead of technical potentials, the efficiency gap lessens or disappears—or, in some cases, actual emissions reductions are greater than predicted. See especially Section 6.2.3, p. 272, for a more detailed description of these research studies and relevant citations.

Major uncertainties

Uncertainties arise from the lack of needed social science research in these areas as well as from identifying other areas that would benefit from people-based research into carbon mitigation.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There are promising areas of research with positive results in at least four areas of energy efficiency, leading to an assessment of high confidence.

Summary sentence or paragraph that integrates the above information

Promising people-based research covered for Key Finding 3 exists as approaches to increase efficiency and thus reduce emissions along supply chains, implement codes and standards for buildings and technologies, understand the variation in energy use among groups and in different places, and include energy-use practices in planning for new technologies or processes. Thus, a level of high confidence is warranted.

KEY FINDING 4

Governance Systems—Research that examines governance at multiple formal levels (international, national, state/province, cities, other communities) as well as informal processes will identify overlaps and gaps and deepen understanding of effective processes and opportunities involved in carbon management, including a focus on benefits such as health, traffic management, agricultural sustainability, and reduced inequality *(medium confidence)*.

Description of evidence base

As global, "top-down," effective climate change or carbon management policy has proven elusive and likely not to meet goals, Key Finding 4 shows that attention has turned to governance (but not limited to formal governments), including networks, social processes, cultural norms and values, and multilevel steering institutions. In urban areas and agricultural spaces, this research has proven fruitful in identifying insights into how policies are formed and implemented as people pursue their own goals while changing in response to economic, regulatory, and other social changes. Research shows that co-benefits are often important—benefits such as health, traffic management, comfort and convenience, agricultural sustainability, and reduced inequality. See Section 6.3, p. 274, for a more detailed description of governance systems research and relevant

citations. Each place or network or governance arrangement is a complex system, but patterns can be discerned. Analysis of social, technological, and ecological circumstances can lead to tailored approaches and pathways to effective carbon management. See Section 6.6, p. 279; Section 6.7, p. 280; and Section 6.8, p. 282, for more detailed descriptions of the evidence base for Key Finding 4, as well as relevant citations.

Major uncertainties

Uncertainties arise from the diverse circumstances of places and societies. Research may not identify important factors in candidate strategies for carbon management, even with the knowledge that "one size does not fit all."

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Research confirms the importance of governance. However, because of the complexity and diversity of different societies in different places, and at least the partial lack of research to identify patterns of governance important for carbon management, a level of medium confidence has been assessed.

Summary sentence or paragraph that integrates the above information

Both formal and informal governance are important for the prospects of carbon management. However, variations in social institutions, culture, and values influence the effectiveness of governance. Hence, the difficulties in complex systems analysis bring uncertainty into the prospects for effective carbon management. Thus, Key Finding 4 has been assessed as having medium confidence.

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7 Tribal Lands

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KEY FINDINGS

1. Many Indigenous peoples in North America follow traditional agricultural and land-use practices that govern carbon cycling on tribal lands. These practices include no-till farming; moving domesticated animals seasonally in accordance with forage availability; growing legumes and cover crops; raising crops and livestock native to ancestral landscapes; and managing forests sustainably with fire, harvest, and multispecies protection.

2. Scientific data and peer-reviewed publications pertaining to carbon stocks and fluxes on Indigenous (native) lands in North America are virtually nonexistent, which makes establishing accurate baselines for carbon cycle processes problematic. The extent to which traditional practices have been maintained or reintroduced on native lands can serve as a guide for estimating carbon cycle impacts on tribal lands by comparisons with practices on similar non-tribal lands.

3. Fossil fuel and uranium energy resources beneath tribal lands in the United States and Canada are substantial, comprising, in the United States, 30% of coal reserves west of the Mississippi River, 50% of potential uranium reserves, and 20% of known oil and gas reserves, together worth nearly $1.5 trillion. Fossil fuel extraction and uranium mining on native lands have resulted in emissions of carbon dioxide and methane during extraction and fuel burning. Energy resource extraction on tribal lands also has resulted in substantial ecosystem degradation and deforestation, further contributing to carbon emissions.

4. Renewable energy development on tribal lands is increasing but is limited by federal regulations, tribal land tenure, lack of energy transmission infrastructure on reservations, and economic challenges.

5. Colonial practices of relocation, termination, assimilation, and natural resource exploitation on native lands have historically hindered the ability of Indigenous communities to manage or influence land-use and carbon management both on and off tribal lands. These factors combined with contemporary socioeconomic challenges continue to impact Indigenous carbon management decision making.

6. The importance placed on youth education by Indigenous communities creates opportunities for future generations to sustain and pass on traditional knowledge important to managing carbon stocks and fluxes on native lands.

Note: Confidence levels are provided as appropriate for quantitative, but not qualitative, Key Findings and statements.

7.1 Introduction

"Indigenous peoples in North America have a long history of understanding their societies as having an intimate relationship with their physical environments. Their cultures, traditions, and identities are based on the ecosystems and sacred places that shape their world. Their respect for their ancestors and 'Mother Earth' speaks of unique value and knowledge systems different than the value and knowledge systems of the dominant United States settler society. … Some Indigenous people believe that human and nonhuman individuals come from the earth and the ability to reach harmony among individuals is dependent on being a steward of the natural environment by giving back more than what is taken" (Chief et al., 2016).

This chapter discusses how diverse Indigenous peoples in the United States, Canada, and Mexico affect and are affected by carbon cycle processes, and it explores the unique challenges and opportunities these communities have in sustaining traditional practices that are inherently tied to carbon stocks and fluxes on a range of landscapes. Carbon fluxes on tribal lands likely differ from those on analogous non-tribal land types (e.g., non-tribal forested, coastal, aquacultural, grassland, and agricultural lands) due to generations of Indigenous people

following traditional agricultural and land-use practices. These practices, referred to as "traditional knowledge," are rooted in an Indigenous worldview that holds humans responsible for the stewardship of all elements of the living and nonliving world around them. This chapter compares traditional agricultural, land-use, and natural resource stewardship practices with those introduced to North America by European settlers to estimate carbon fluxes on tribal lands relative to similar non-tribal land types.

Intrinsic differences in traditional and historical land-use practices on and off tribal lands can inform understanding of the carbon cycle and are the basis for considering tribal lands as a focused topic in this report. The lack of direct measurements of carbon stocks and fluxes on tribal lands requires that carbon cycle impacts associated with traditional practices be considered in comparison with non-tribal practices on similar land types, as data do not yet exist for creating tribal land carbon budgets. Formidable challenges resulting from the inclusion in this report of geographically and culturally diverse Indigenous peoples across North America are acknowledged. However, outlining opportunities for further exploration of traditional practices and how they could influence the carbon cycle is essential. Both the challenges and opportunities set the stage for identifying research needs that may empower Indigenous communities to expand their influence on decision making, affecting carbon management both on and off of tribal lands. Case studies are used to illustrate how traditional forestry, livestock, and crop production practices can impact carbon stocks and fluxes. Contributions to the carbon cycle from past and ongoing fossil fuel and uranium energy extraction and the role of renewable energy production on tribal lands also are covered.

7.1.1 Indigenous and Eurocentric Worldviews

The worldview of native communities (collectively referred to in this chapter as "Indigenous peoples") from the United States, Canada, and Mexico is ecosystem- and watershed-based, inextricably bound to the land, and thus intimately connected to ecological systems integral to the carbon cycle. Management of carbon stocks and fluxes is encompassed within, and not easily separated from, the overall Indigenous perspectives that holistically link human and ecological health. These perspectives fundamentally differ from the Eurocentric worldview introduced to North American landscapes with the influx and migration of European settlers across the continent. A meaningful (albeit simplified) contrast between Indigenous and Eurocentric worldviews underpins the different approaches tribal and non-tribal communities have toward living on the land, which, in turn, influences how they manage carbon stocks differently on similar land types. Indigenous worldviews are rooted in a communal, spiritual, and cultural sense of place built on a web of connections between humans (living and ancestral) and nature (animals, plants, and minerals). Traditional agrarian practices are based on significant horticultural advancements using grouped planting strategies. One example is the "Three Sisters" agricultural system of mound structures in the eastern United States, where the climate is wetter. Another example involves planting seeds deeply in sand in the arid, rainfed agriculture of the western United States. These practices are native to ancestral landscapes and ecosystems and have integral ties to ceremonial practices and seasonal cycles. In contrast, Eurocentric worldviews are more uniformly applied and were built on the notion of altering the natural world. Agricultural practices introduced to North America by European settlers rely heavily on plowing or tilling fields, which required making significant changes to the land by clearing vegetation, including clearcutting forests, to accommodate planting.

Traditional practices tied to a holistic approach to living in balance with the drivers of air, land, and watershed change are fundamental for Native American tribes in the United States, First Nations Aboriginal peoples in Canada, and Ejido communities in Mexico (Chief et al., 2016; NCAI 2015; Blackburn and Anderson 1993). These communities have ancestral ties to the land that span thousands of years. Many Indigenous communities are agrarian based, with their livelihoods and cultural

identity intimately associated with the health and well-being of the plants, fish, animals, and natural resources of their ancestral homelands (see Figure 7.1, p. 307). Livestock grazing and crop production; seed, nut, and plant gathering; and fishing and wildlife hunting are essential for cultural ceremonies, community wellness, and economic prosperity (AANDC 2013; Assies 2007; Chief et al., 2016; Tiller 1995, 2015).

7.1.2 Carbon Cycling Considerations Unique to Tribal Lands

Carbon cycling among reservoirs in the atmosphere, terrestrial vegetation, soils, freshwater lakes and rivers, ocean areas, and geological sediments is integral to native landscapes. That said, discussions about how Indigenous peoples are affected by carbon cycle processes are different from similar discussions related to non-tribal lands, thus warranting separate consideration due to several key factors:

- Scientific data and peer-reviewed publications pertaining to carbon stocks and fluxes on reservation lands are virtually nonexistent, which makes establishing accurate baselines for carbon cycle processes problematic.
- Traditional knowledge about practices with bearing on carbon stocks on native lands (e.g., intergenerational stories, practices, and observations) often does not conform to mainstream science prescriptions for data gathered and analyzed for technical reports, including this report.
- Indigenous communities throughout North America are culturally distinct, with their own languages, practices, spiritual and cultural systems, governance structure, and deep connections to their lands, hence generalizations across North America may be of limited value.
- Native American communities in the United States and First Nations of Canada (but not Ejidos in Mexico) are recognized as sovereign nations with their own distinct policies, laws, and practices that may impact carbon stocks and fluxes on native lands.
- Native communities are heavily affected by the policies and laws of surrounding national, state, provincial, and local governments, as well as the economic and social drivers of non-tribal landowners and energy and natural resource extraction industries. Land-use decisions by native communities are influenced by high levels of poverty, unemployment, and health challenges.
- Complex Native American land tenure and water rights laws enacted by the U.S. and Canadian governments during the last two centuries have fractionated tribal land ownership, producing checkerboards of land types on reservations. In the United States, some of these lands are held "in trust" by the federal government, while others have been allotted or sold as "fee simple" lands that may be owned by one or many tribal or non-tribal individuals and subject to both tribal and non-tribal laws (Colby et al., 2005; McCool 2002; NCAI 2015; Pevar 2012; Thorson et al., 2006).

Opportunities for managing carbon stocks and fluxes present unique challenges to Indigenous peoples because of external stressors that constrain or complicate a community's ability to sustain traditional practices that affect carbon processes. These include:

- The historical practice by the U.S. and Canadian governments of relocating Indigenous peoples from their expansive ancestral homelands to reservations on "marginal lands" in remote areas, which may or may not be contiguous with their sacred places. Similar disenfranchisement of Ejido communities has occurred in Mexico, where these isolated communities have little or no self-governance (OHCHR 2011; Pevar 2012; Russ 2013).
- Close cultural and economic ties to natural resources, geographic remoteness, and

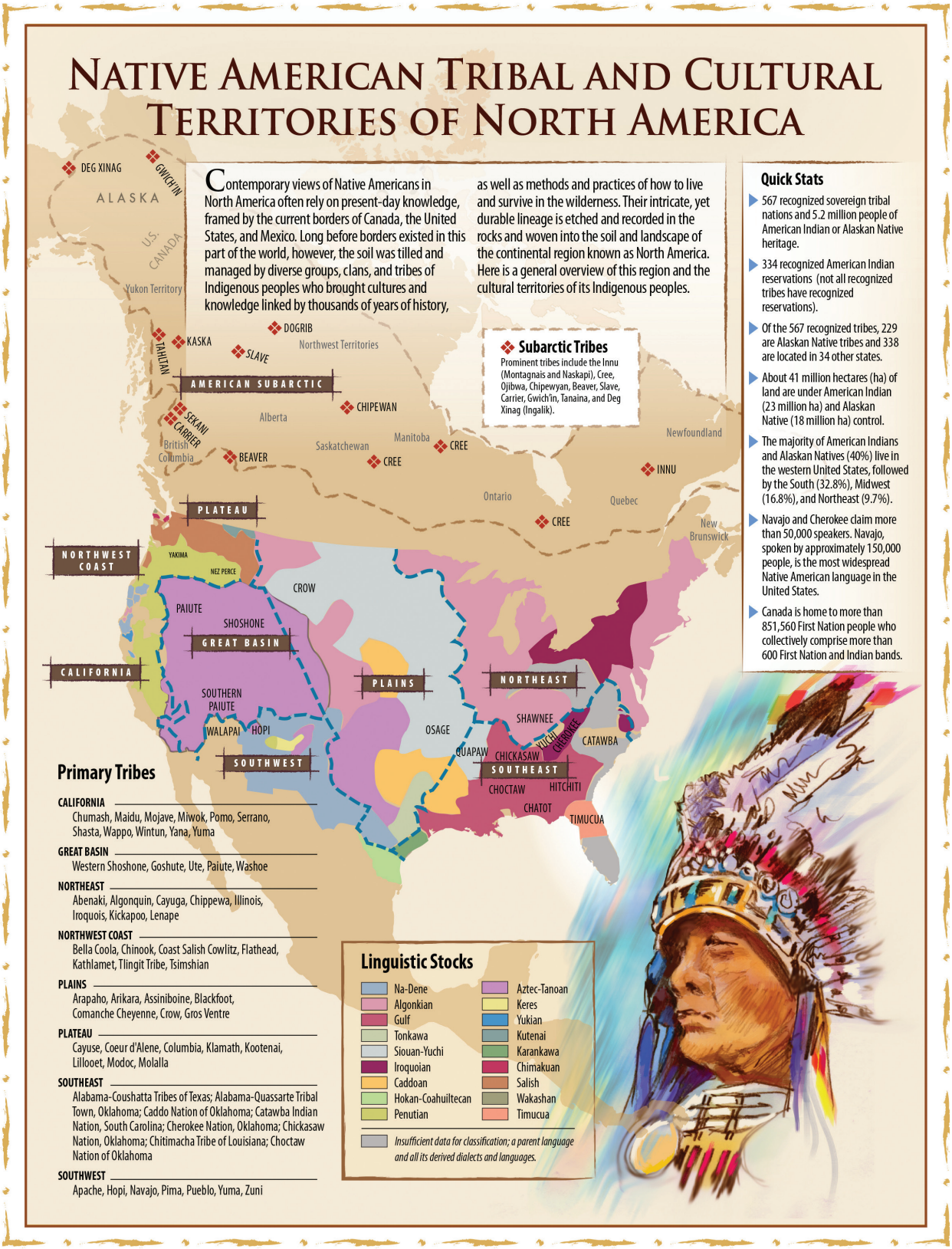

Figure 7.1. Native American Tribal and Cultural Territories of North America. Overview of primary tribes, linguistic stocks, and extent of ancestral homelands. [Figure source: Ron Oden, University of Nevada, Reno. Data sources: NCAI 2015; Prine Pauls 2017; Sturtevant 1991; U.S. Census Briefs 2012; U.S. EIA 2017a.]

economic challenges make Indigenous peoples among the most vulnerable populations to climate change. These include (but are not limited to) tribes being displaced by rising sea levels and thawing tundra and those subjected to increased heatwaves, droughts, and extreme weather events that disrupt the traditional seasonal cycle and affect native fish, plant, animal, and water resources (Bennet et al., 2014; Melillo et al., 2014; Redsteer et al., 2018; Krakoff and Lavallee 2013).

- Colonial practices of relocation, termination, assimilation, and coercive exploitation of native lands have divided Indigenous communities and limited their ability to influence surrounding national and regional government decision making related to land use and carbon cycling (Anderson and Parker 2008; Bronin 2012).

- European settlement mandated that native communities convert traditional agriculture practices to Eurocentric crop and livestock production, which forced changes in landscapes, water supplies, and community health (Reo and Parker 2013; Kimmerer 2003; Thorson et al., 2006).

- Daunting socioeconomic challenges, including high levels of poverty and disease, demand significant time, attention, and resources and can influence land-use decision making by individuals and tribal governments. Native communities are heavily reliant on a wage economy and are subject to different federal policies than other citizens in their respective countries. The poverty rate for Native Americans living on reservations in the United States is 39% (the highest in the country), the joblessness rate is 49%, and the unemployment rate is 19%. Native health, education, and income statistics are likewise lower than those for any other racial group in the United States (NCAI 2015, 2016; GAO 2015; Indigenous Environmental Network 2016; Mills 2016; Regan 2016; Royster 2012; Notzke 1994; Assies 2007; Frantz 1999).

7.2 Historical Context and North American Perspective

Short summaries of Indigenous peoples of North America (United States, Canada, and Mexico) that are relevant to this report are provided in this section. See Appendix 7A: Summary Descriptions of Indigenous Communities in North America, p. 331, for additional details and references.

7.2.1 Governance and Population

Today, federally recognized Native American tribes operate under a government-to-government relationship with the U.S. government. First Nation tribes have similar self-government status within Canada. Mexico has no established system of reservations or formal system of Indigenous community self-government.

According to the 2010 Census, the United States is home to 5.2 million people of American Indian or Alaskan Native heritage. Together, they comprise the 567 federally recognized tribes in 35 U.S. States, 229 of which are in Alaska and the remaining 338 in 34 other states (NCAI 2015; U.S. Census Briefs 2012). About 41 million hectares (ha) are under American Indian or Alaskan Native control, with approximately 5.2 million people identified as American Indian/Alaskan Native (alone or in combination with other races). Approximately 22% of Native Americans live on tribal lands and 78% live in urban or suburban environments, with 19.5% of Native people living in Alaska (Norris et al., 2012).

According to the 2011 National Household Survey, Canada is home to 851,560 First Nation people that collectively comprise more than 600 First Nation and Indian bands. First Nation people make up about one-third of the total population in the Northwest Territories and one-fifth of the population in the Yukon (Statistics Canada 2011). Nearly half of those registered under Canada's Indian Act (49.3% or 316,000) live on reserves or Indian settlements (Statistics Canada 2011).

Indigenous communities in Mexico number 16.9 million people, the largest such community in North

America. Although Mexico does not have a system of reserves or reservations for Indigenous people, the majority (80%) of all people who speak an Indigenous language live in the southern and south-central regions of Mexico (Cultural Survival 1999; Minority Rights Group International 2017).

7.2.2 Land Use: Agriculture and Energy Extraction and Production

United States

Agriculture is an important industry for Native Americans across the United States, providing more than $1.8 billion in raw agricultural products in 2012 from 20.6 million ha of farmland ($700 million from crop sales and $1.1 billion from livestock; USDA 2014). About 80% of tribal agriculture occurs in seven states: Arizona, Oklahoma, New Mexico, Texas, Montana, California, and South Dakota (USDA 2014). Coal, natural gas, and oil reserves present opportunities for an estimated $1 trillion in revenue from mining and energy production across U.S. tribal lands (NCAI 2016), and commercial fisheries, forestry, tourism, energy extraction and generation, and other industries offer other opportunities for economic growth (see Figure 7.2, p. 310). Tribal lands emit a significant amount of carbon today, largely due to a history of federal policies of fossil fuel resource development on Native American reservations. Coal strip mining on Hopi, Navajo, and Crow tribal lands supply coal-fired power plants on and near these reservations, contributing to U.S. carbon emissions (U.S. EIA 2015; Krol 2018).

The National Indian Carbon Coalition (NICC) is one organization explicitly dedicated to engaging Native American communities in carbon management (NICC 2015). NICC is a greenhouse gas (GHG) management service established to encourage Native American community participation in carbon cycle programs with the goal of furthering both land stewardship and economic development on Native American lands. NICC was created as a partnership between the Indian Land Tenure Foundation and the Intertribal Agriculture Council to assist tribes in developing carbon credit programs. With waning U.S. interest in adopting a carbon credit economy, NICC may be less impactful than originally envisioned. However, NICC-sponsored programs represent focused efforts on carbon sequestration; GHG emission reductions; and the promotion of soil health, ecological diversity, and water and air quality in the context of traditional values and economic development. If the United States chooses to pursue a carbon credit economy in the future, programs such as NICC will be invaluable in positioning Native American communities to participate and benefit socially, culturally, and economically.

Land tenure; federal regulations, policies, and laws; and cultural values have made the extraction of fossil energy, uranium, and other mineral resources on tribal lands a socially and economically complex issue. The history of natural resource development on reservation lands, as well as policies such as the Indian Mineral Leasing Act, have led to a dependence on nonrenewable resources and narrowed the economic focus for revenues supporting many tribal governments (Krakoff and Lavallee 2013). As mentioned, Native American communities are among the nation's poorest, with nearly 40% of people on reservations living in poverty (four times the national average) and average annual incomes less than half those of other U.S. citizens (Grogan 2011). Such socioeconomic challenges have been attributed with motivating some tribes to allow extraction of their mineral and fossil fuel resources (Regan 2014). The U.S. Energy Information Administration (EIA) documents the energy profiles for each U.S. state and territory and updates them monthly, including descriptions of energy extraction and use on tribal lands (U.S. EIA 2017a).

Fossil fuel and uranium energy resources beneath tribal lands are substantial, comprising 30% of the nation's coal reserves west of the Mississippi River, 50% of its potential uranium reserves, and 20% of its known oil and gas reserves, together worth nearly $1.5 trillion (Grogan 2011). Most of these resources are concentrated with a few tribes in the western United States (Grogan 2011; Regan 2014;

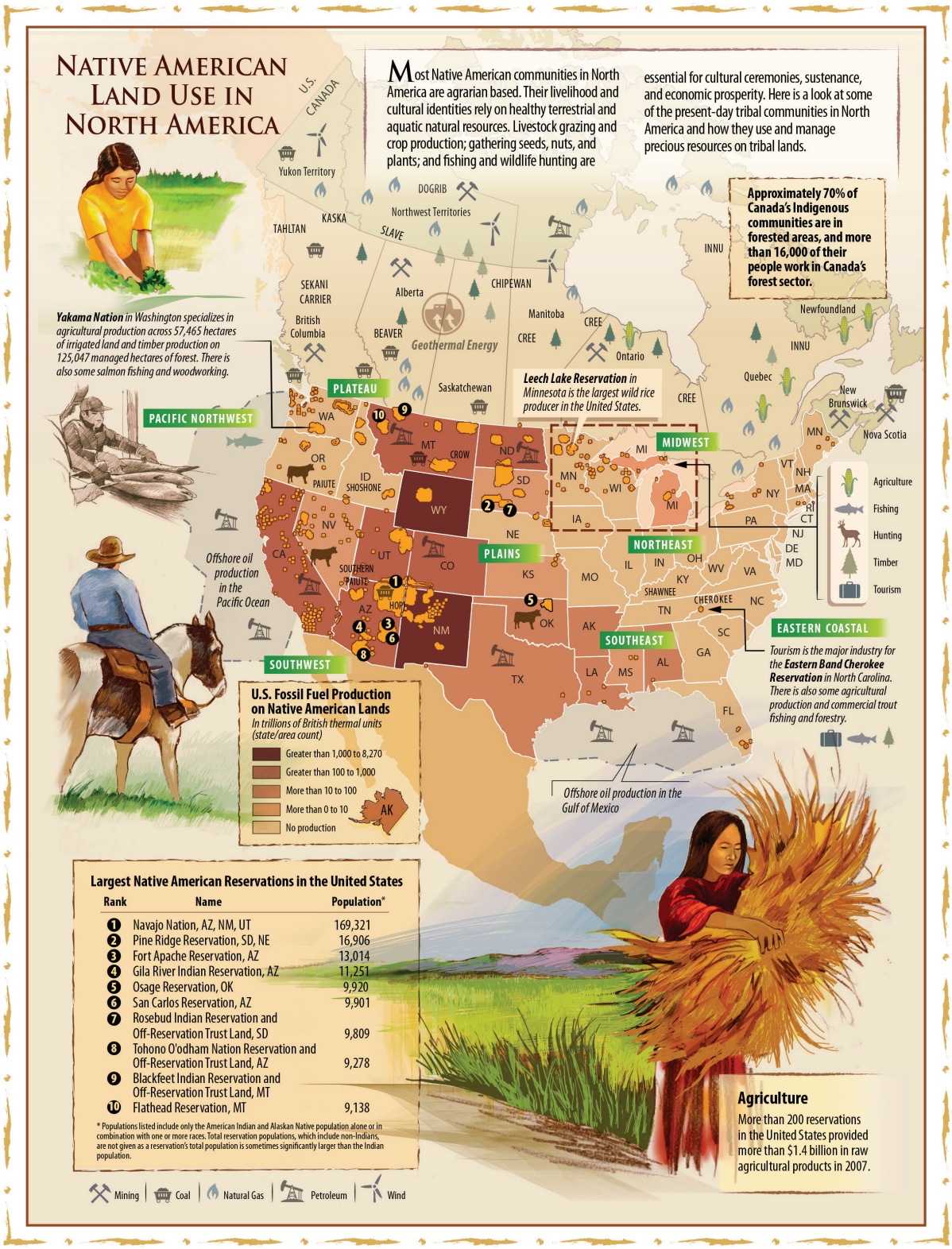

Figure 7.2. Native American Land Use in North America. The size, scale, and location of some Native American reservations in the conterminous United States are shown, along with tribal fossil fuel production, population statistics, dominant industries by region, major socioeconomic drivers, and traditional practices (e.g., agriculture, hunting, and fishing). Coal strip mining on Hopi, Navajo, and Crow tribal lands supply coal-fired power plants on and near these reservations, contributing to U.S. carbon emissions. [Figure source: Ron Oden, University of Nevada, Reno. Data sources: NCAI 2015; Prine Pauls 2017; Sturtevant 1991; U.S. Census Briefs 2012; U.S. EIA 2017a; Natural Resources Canada 2016a.]

Table 7.1. Energy Resources on Tribal Lands in the United States[a]

Tribe	Fossil Fuel and Uranium Resources
Hopi (Arizona)	Coal, oil, and gas
Navajo (Arizona and New Mexico)	Coal, oil, gas, and uranium
Southern Ute (Colorado)	Coal, oil, and gas
Ute Mountain (Colorado)	Coal, oil, gas, and uranium
Blackfeet (Montana)	Coal, oil, and gas
Crow (Montana)	Coal, oil, and gas
Assinboine and Sioux (Montana)	Coal, oil, and gas
Northern Cheyenne (Montana)	Coal and oil
Jicarilla Apache (New Mexico)	Coal, oil, and gas
Three Affiliated Tribes (Fort Berthold, North Dakota)	Coal, oil, and gas
Osage (Oklahoma)	Oil and gas
Uintah and Ouray Ute (Utah)	Coal, oil, gas, and oil shale
Arapaho and Shoshone of Wind River (Wyoming)	Coal, oil, gas, and uranium

Notes

a) Regan 2014

see Table 7.1, this page; see also Ch. 3: Energy Systems, p. 110, for information about non-tribal energy extraction). Conflicts between traditional values and the need for economic development are demonstrated by uranium extraction on Navajo lands, where nearly 30 million tons were removed from over 1,000 mines from 1944 to 1986. Half of these mines are abandoned and awaiting remediation (U.S. EIA 2017b; U.S. EPA 2018; Moore-Nall 2015). Uranium mining provided some short-term benefits from mining income and jobs but resulted in extreme ecological degradation and long-term impacts to water, public health, and soil carbon sequestration (Brugge and Goble 2002; Diep 2010).

Recent discussions have emerged regarding strategies and policy tools that tribal governments could adopt in transitioning to carbon-neutral development and climate action plans (Suagee 2012). These strategies include updating substandard tribal housing and building new homes for the unmet housing need by addressing the lack of inclusion of federally recognized tribes in the U.S. Energy Independence and Security Act of 2007 (Public Law 110–140). Although this law requires housing to conform to an Energy Conservation Code, its application to tribal housing is generally lacking in order to limit the cost of such housing, leaving Native American home occupants with higher energy bills. The Indian Tribal Energy Development and Self-Determination Act provides additional frameworks for developing energy infrastructure (Anderson 2005), but the current legal framework does not adequately address tribal needs (Bronin 2012). The financial dependence of some tribes on fossil fuel extraction is a significant barrier to embracing carbon-neutral practices, especially when tribes are excluded from alternative energy tax credit incentives. For example, 85% of Hopi tribal revenues are from strip mining coal (Krol 2018). Moreover, rigorous studies on land-use impacts to ecosystems on tribal lands would help inform and motivate tribal governments to consider energy alternatives. Other challenges include environmental concerns, such as a lack of rigorous studies on land-use impacts to local ecosystems and the exclusion of tribes from incentives such as tax credits that are available to other entities developing alternative energy projects.

Canada

Indigenous communities in Canada rely heavily on sustenance and production agriculture (i.e., crops and livestock); fishing and hunting; forestry and timber harvesting; coal, oil, and gas extraction; and some alternative energy production (Canada Energy and Mines Ministers' Conference 2016; Merrill and Miro 1996; Natural Resources Canada 2016b). These activities, along with tourism, are the major economic drivers for tribal communities. Typically, Indigenous lands are sparsely populated with few (if any) commercial industries except those associated with gaming.

Forests and forest resources offer economic opportunities for the First Nations in Canada (Natural

Resources Canada 2016a). The Canadian government's Aboriginal Forestry Initiative provides information and support for Aboriginal forestry projects, as well as more than $10 million in funding opportunities across Canada for First Nations, which control more than 3,000 ha of forested land. Approximately 70% of Canada's Indigenous communities are in forested areas, and more than 16,000 Aboriginal people have worked in Canada's forest sector since 2011 for projects across the country (Natural Resources Canada 2016a).

Mining occurs on many First Nation lands, with over 480 mining agreements for more than 300 projects signed between mineral companies and Indigenous groups since 1974. As of December 2015, 380 projects were active (Canada Energy and Mines Ministers' Conference 2016). In the oil sands region of northern Alberta, some Indigenous communities are concerned about the environmental impacts of development, but the oil sands industry also provides economic opportunities for Indigenous-owned businesses that provide goods and services to oil sands companies (Natural Resources Canada 2016b). Fisheries are a traditional and modern source of livelihood for many Aboriginal people, especially in western Canada, where food fishing and commercial fishing are highly important (Notzke 1994).

Mexico

Temperate and tropical forests make up 56.8 million ha or 40.1% of Mexico's land area. Land reforms following the Mexican Revolution of the early 1900s put more than half the country's forested lands in the hands of "Ejidos" (communally owned farming collectives) and Indigenous communities (Bray et al., 2003). The result created community forest enterprises (CFEs), through which local communities own, manage, and harvest their own forest resources including timber. Although not all CFEs are well managed, they have the potential to provide income for poor, rural communities while delivering ecological services and maintaining forest productivity and biodiversity (Bray et al., 2003). The Mexican government initially owned Ejido lands, but a constitutional amendment in 1992 gave the farming collectives formal titles to their own lands (Merrill and Miro 1996).

7.3 Current Understanding of Carbon Stocks and Fluxes

Due to many of the factors previously cited, especially the lack of explicit measurements and data for carbon cycle processes, a quantitative assessment of the carbon stocks and fluxes for Indigenous lands does not presently exist. However, comparisons can be made about carbon cycling between tribal lands and similar, non-tribally managed land types (e.g., rangelands, agricultural lands, and forests). Comparing and contrasting carbon cycling impacts resulting from traditional practices on tribal lands with Eurocentric-based land-use practices on (and off) tribal lands could prove beneficial in developing more effective carbon management programs for both tribal and non-tribal lands. As in all systems, integrating scientific, social, and economic perspectives into strategies to use and protect natural resources and sustain healthy landscapes will be valuable to communities closely tied to the land.

Several case studies are presented throughout the rest of this section to illustrate 1) the role of Indigenous agricultural practices in maintaining or enhancing carbon sequestration on tribal lands, 2) the impacts of European settlement on traditional agriculture, 3) the role of Indigenous forest management approaches for sustaining forest health, and 4) the impact of fossil fuel and uranium extraction on tribal land carbon emissions, as well as the potential for renewable energy production.

7.3.1 Role of Indigenous Agricultural Practices in Maintaining or Enhancing Carbon Sequestration

Carbon can be stored above and below ground in vegetation (live or dead) and in soils on tribal lands such as agricultural lands, rangelands, aquacultural systems, and forests (Zomer et al., 2017; Baker et al., 2007). Compared to surrounding non-Indigenous lands, agricultural (crop and livestock) practices on

tribal lands tend to be significantly less intensive, with extensive reliance on free-range grazing, dry-land farming, and no-till cropping especially in arid regions (Ingram 2015; Teasdale et al., 2007; Wall and Masayesva 2004; Kimmerer 2003). Because these traditional practices are less disruptive to native ecosystems, they tend to conserve carbon stocks on the landscape (Baker et al., 2007; West and Post 2002). However, compared to agriculture on non-tribal lands, traditional practices also may reduce economic output from crop production, cattle-carrying capacity on rangelands, and timber harvests (Drinkwater et al., 1998; Gabriel et al., 2006). Therefore, carbon inventories on native lands reflect a balance between sustaining traditional practices and the adoption of more intensive Eurocentric agricultural practices to increase trade and income.

The colonial-driven transformation of human and natural systems that pushed Native American communities to marginal areas and forced tribes onto restrictive reservations with limited options for food and safety (Lynn et al., 2013; Reo and Parker 2013), coupled with the introduction and adoption of Eurocentric agriculture, crops, and land-use practices, has (in many cases) led to desertification, soil degradation, erosion, and deforestation on tribal lands. These impacts, in turn, may have reduced the carbon-carrying capacity of the soils and vegetation (Redsteer et al., 2010; Baker et al., 2007; Kane 2015; Schahzenski 2009). Alfalfa, an introduced perennial crop with a deep root structure, is a dominant production crop and economic driver for many tribes in the arid southwestern United States (USDA 2014; U.S. Census Briefs 2012). Continuous alfalfa planting has been shown to contribute to the accumulation of soil organic carbon and total nitrogen under certain temperature and precipitation conditions (Chang et al., 2012). Overall, tribal and non-tribal carbon fluxes for multiple types of agriculture are probably close to net neutral in areas where both traditional and introduced agricultural practices are in use (see Ch. 5: Agriculture, p. 229). An exception is the continued use of slash-and-burn practices by some communities in Mexico (Bray et al., 2003; Deininger and Minten 1999).

Case Studies Utilizing Traditional Farming Practices for Carbon Sequestration

"For millennia, from Mexico to Montana, women have mounded up the earth and laid these three seeds (corn, beans, and squash) in the ground, all in the same square foot of soil. When the colonists on the Massachusetts shore first saw Indigenous gardens, they inferred that the savages did not know how to farm. To their minds, a garden meant straight rows of single species, not a three-dimensional sprawl of abundance. And yet they ate their fill and asked for more, and more again" (Kimmerer 2003).

Carbon sequestration projects on agricultural lands can be realized through improved management of fertilizer applications, erosion mitigation, return to no-till or reduced-tillage farming methods (depending on location), restoration of riparian areas, grazing management plans, good livestock waste management, and other measures (Zomer et al., 2017; West and Post 2002; Baker et al., 2007; see Ch. 5: Agriculture, p. 229, and Ch. 12: Soils, p. 469, for more information on no-till agricultural impacts on carbon sequestration). In southwestern Oklahoma, NICC worked with the Comanche Nation to establish a new agriculture leasing management system across 40,000 ha of allotments and tribal-owned land. Actions that could prove to be carbon sequestration measures on this reservation include a return to no-till farming, establishment of shelterbelts to prevent wind erosion, and rotational grazing management plans (NICC 2015).

On rangelands, overgrazing, soil erosion, wildfires, offroad driving, and conversion of rangeland to farmland can release carbon into the atmosphere, but carbon also can be sequestered through sustainable land management practices. On the Santa Ana Pueblo reservation in New Mexico, NICC worked with tribal members to improve land management for carbon sequestration across 4,000 ha. Provisions included increasing vegetation cover to prevent soil erosion, decreasing the density of woody species

to prevent wildfires, minimizing offroad driving, and developing and implementing livestock grazing plans (NICC 2015). On prairie lands, the Inter-Tribal Buffalo Council is a collaborative among 58 tribes in 19 states dedicated to restoring bison to Indigenous communities to promote Native American culture and spiritual practices, ecological restoration, and economic development. Bison have a smaller ecological impact on prairie lands than cattle, and their reintroduction by Indigenous communities in the Great Plains (albeit on a small scale compared to cattle ranching) is contributing to prairie restoration (Kohl et al., 2013).

There are data from across all of North America on traditional (Indigenous) agricultural practices going back several thousand years. Both oral tradition and written accounts dating from the 1500s show evidence of agricultural practices that are now being examined as a meaningful contribution to "carbon farming" or carbon sequestration via agricultural practices. These practices include no-till seeding, use of organic mulches (wood wastes and straw), use of composts (nonconsumed plant parts and animal wastes), moving domestic animals among areas based on season and forage availability, use of legumes (nitrogen-fixing plants), and complex cropping such as planting corn in perennial fields of clover or vetch (Baker et al., 2007; Drinkwater et al., 1998; Gabriel et al., 2006).

It has long been known that soil organic matter contains one of the planet's largest carbon sinks (see Ch. 12: Soils, p. 469; Zomer et al., 2017; Kane 2015; Marriott and Wander 2006; Teasdale et al., 2007). Various organizations, including Nourishing Systems in Oregon, are working to refine traditional methods of composting and soil carbon enrichment (Goode 2017). This approach, inspired by the Buffalo Dance tradition of the Northern Plains Tribes, is designed to mimic the soil nutrient cycling resulting from buffalo roaming on tallgrass prairie lands. Sunflower stalks, which are porous and recalcitrant (rich in lignin and therefore slowly degrading), are used as the base layer in the trenches between row crops and perennials (see Figure 7.3, p. 315). Less recalcitrant cellulosic wastes such as straw are placed on top of the sunflower stalks. As the final layers, wastes or the nonedible portions from crops are added as compost. These filled trenches are covered and used as walkways as the soils are enriched slowly by the decay of the organic matter, and the soil ecological assemblage of microorganisms, insects, and worms cycle the carbon and nutrients within the soil subecosystem (Goode 2017; Schahzenski and Hill 2009; West and Post 2002). A key to soil carbon sequestration may be a switch of the mechanisms that move soils away from bacterial dominance toward fungal dominance (Johnson 2017). At least in some systems, this change in soil community can result in increased soil fertility and water storage capacity, plant water-use efficiency, and soil nutrient availability to plants. The process also reduces plowing and tillage costs, fertilizer and pesticide applications, and water (both surface and groundwater) pollution (Johnson 2017).

"In Indigenous agriculture, the practice is to modify the plants to fit the land. As a result, there are many varieties of corn domesticated by our ancestors, all adapted to grow in many different places. Modern agriculture, with its big engines and fossil fuels, took the opposite approach: modify the land to fit the plants, which are frighteningly similar clones" (Kimmerer 2003).

The Pueblo Farming Project (Bocinsky and Varien 2017; Ermigiotti et al., 2018) has documented the drought resiliency of traditional Hopi farming practices, including the development of drought-tolerant Hopi corn varieties and dryland (non-irrigated) farming. An ongoing collaboration between the Hopi tribe and the Crow Canyon Archaeological Center in Cortez, Colorado, the Pueblo Farming Project has planted, tended, and harvested experimental gardens in southwestern Colorado every summer since 2008 to investigate the viability of growing Hopi maize outside of the Hopi mesas in northern Arizona. Traditional Hopi farmers grow their corn using entirely manual cultivation practices: a digging stick, a gourd of water, and seed corn selected to meet the subsistence and ritual needs of the Hopi community (Wall

(a)

(b)

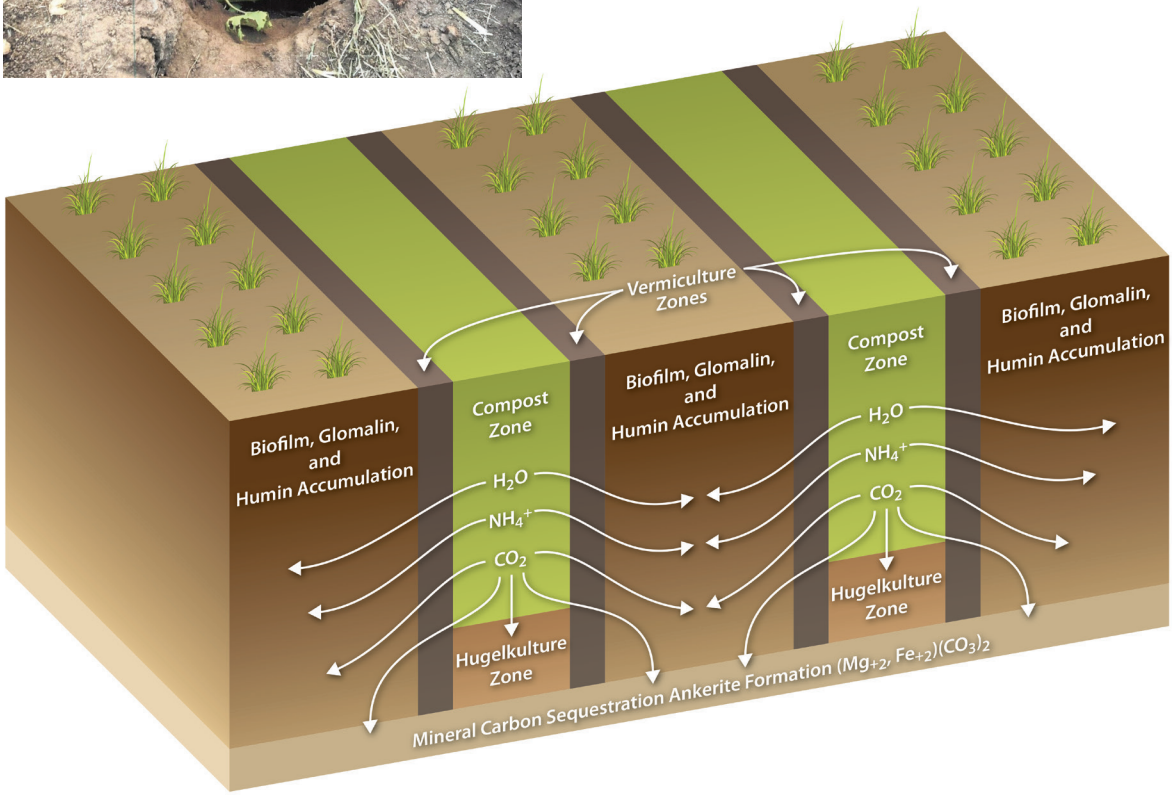

Figure 7.3. Traditional Composting and Soil Carbon Enrichment. (a) Trenched complex compost for soil carbon accumulation in soil organic matter (SOM). **(b)** SOM development using trench composting. Key: H_2O, water; NH_4^+, ammonium; CO_2, carbon dioxide. [Figure source: Scott Goode, Desert Research Institute.]

and Masayesva 2004). With no tilling or tractors and minimal water inputs, Hopi corn farming maximizes moisture, nutrient, and carbon storage in the sandy soils of the Hopi mesas. As Hopi oral history attests and archaeologists have documented, traditional Hopi corn farming has sustained the Hopi community and their ancestors for millennia (Bocinsky and Varien 2017; Coltrain and Janetski 2013; Cooper et al., 2016; Matson 2016).

7.3.2 Impacts of European Settlement on Traditional Agriculture

For tribal communities that have adopted Eurocentric crop and livestock agricultural practices, carbon fluxes likely are comparable to fluxes from adjacent, non-tribal lands, including carbon losses due to soil erosion and desiccation. Before the 1860s, Navajo Nation families lived on a subsistence mix of farming, hunting and gathering, and herding livestock. This subsistence mix required families to range widely over a vast area of traditional Navajo lands (Fanale 1982). Families moved their livestock around core grazing areas shared by networks of interrelated, extended families; during droughts they used other kinship ties to gain access to more distant locations where conditions were better. This land-use regime helped families distribute their livestock over the range as conditions warranted (Redsteer et al., 2010). After the reservation was established in 1868, land-use pressure from non-Native American settlers cut them off from the wettest areas that were best for hunting, gathering, and summer grazing. Navajo families were forced to depend more heavily on farming and especially stock raising within the more arid to semi-arid sections of their homeland (Redsteer et al., 2010). By the early 20th century, both tribal and federal government officials along with other observers were warning about desertification of Navajo ranges (Kelley and Whiteley 1989; White 1983). Stock-reduction programs of the 1930s created further restrictions by establishing grazing districts and requiring each Navajo family to have a permit for raising livestock within a particular district, not to exceed a certain number (White 1983; Young 1961). Erosion has continued to be a problem, though range managers now recognize that climate, landscape conditions, and other hydrological processes also cause regional soil erosion even without additional grazing pressures (Redsteer et al., 2010; White 1983). Currently, the early 20th century grazing policies remain in place, and further revisions to grazing are being proposed as prolonged drought conditions from 1994 to 2018 and increasing aridity continue to degrade rangeland viability, water supplies, and general living conditions (Redsteer et al., 2018).

7.3.3 Role of Indigenous Forest Management Approaches for Sustaining Forest Health

Carbon fluxes between the biosphere and atmosphere may result in net carbon sinks (via carbon sequestration) in areas engaged in sustainable forest management and timber harvesting (see Ch. 9: Forests, p. 365). Numerous Indigenous communities throughout North America have sustainably managed forestlands, which may serve as carbon sinks in both tribal and non-tribal areas. Indigenous forestry practices in some cases have resulted in large and diverse stands of timber (Trosper 2007) that could be evaluated for their carbon storage impacts.

Case Studies of Sustainable Forest Management in the United States, Canada, and Mexico

United States. A renewed focus on traditional values, environmental stewardship, public health, and food sovereignty has led many Native American communities to adopt (or re-adopt) sustainable forest management practices rooted in their traditions and cultures. Exemplifying this renewed focus are the Confederated Salish and Kootenai Tribes (CSKT) of the Flathead Reservation in Montana, who have implemented an ecosystem-based forest management plan (Chaney 2013; CSKT 2000) that uses ecological, cultural, social, and economic principles to maintain and restore the ecological diversity and integrity of forests on the Flathead Reservation. Fire was integral to how the Salish, Kootenai, and Pend d'Oreille tribes managed the forests that provided them with sustenance and livelihood.

The CSKT have reintroduced traditional practices including the use of fire to manage their forests. These practices are enhancing forest ecosystem health and diversity and have reduced the impact of catastrophic wildfires that occurred on neighboring non-tribal federal lands (CSKT 2000). Carbon stocks are affected by the distribution and health of both trees and culturally important understory plants. Although fire can release large amounts of carbon and carbon stocks and fluxes have not been explicitly measured on the Flathead Reservation, the reintroduction of these traditional practices is resulting in more sustainable and healthy forests that are more diverse and fire-resistant.

Prior to European contact, the Salish, Kootenai, and Pend d'Oreille tribes of northwestern Montana (who were subsequently relocated to the Flathead Reservation) derived most of their sustenance from the surrounding forested lands, including culturally significant tree species (e.g., whitebark pine) and understory vegetation (e.g., huckleberries and medicinal plants; CSKT 2000). They used fire to actively manage forests for at least 7,000 years, according to oral tradition. These "Indian-lit fires" were usually set in the cooler days of spring, early summer, and fall when burning conditions were less hazardous; the fires were typically lower in intensity than lightening fires, which usually ignite in the hotter summer season. Using both fire and active harvesting, the tribes managed the forests holistically to balance stand density, understory vegetation health, and animal habitats to support hunting. The fire-exclusion policy introduced by the U.S. government in 1910, as well as the introduction of clearcut logging and cattle grazing, changed the biodiversity and health of these forests. During the last century, many tree stands have grown denser with many trees stressed from lack of water and insect and disease outbreaks. Although carbon stocks may have increased in these forests during this time, the forests are much more susceptible to catastrophic wildfires, as was evident in the summer of 2017 when over 405,000 ha were burned by wildfires in Montana (USDA 2017). Such burns, of course, result in large losses of carbon to the atmosphere.

Carbon sequestration projects involving forested land can also take the form of afforestation projects (i.e., planting trees on land that was previously unforested) or reforestation projects (i.e., planting trees in places where trees were removed). The Nez Perce Tribe of Idaho began an afforestation and reforestation project for carbon sequestration during the 1990s, planting trees on a 160-ha plot of previously unforested land. The tribe has since expanded its efforts to include 33 different afforestation and reforestation projects (including fire rehabilitation projects) covering approximately 1,379 ha (NICC 2015).

Canada. Canadian forest management programs include initiatives to build capacity and allocate revenues from resources shared among First Nations (AANDC 2012). With the emergence of carbon markets as an option for addressing climate change, First Nations formed the First Nations Carbon Collaborative, which is dedicated to building capacity among Indigenous communities to access and benefit from emerging carbon markets (IISD 2010, 2011). A goal of these programs is to address the economic challenges facing these communities by developing revenue-generating activities associated with carbon sequestration through sustainable forest management, restoration, and protection; biomass tree farming; and protection of boreal forest peatlands or "muskegs." The challenges identified by First Nations to engaging effectively in carbon markets are not unlike those faced by Indigenous communities in the United States and Mexico.

Mexico. Ejidos in Mexico are based on traditional Native American land-tenure systems that allow individuals to farm communally owned lands (Bray et al., 2003). An in-depth study analyzing the role of poverty, Ejido land tenure, and governmental policies in stimulating deforestation in Mexico revealed that poverty and government policies to hold maize prices above the world average increased deforestation (Deininger and Minten 1999). In contrast, Ejido communal land-tenure arrangements did not directly affect deforestation rates, and, within the Ejidos, Indigenous communities were associated with lower deforestation rates. Although several

factors likely contribute to this finding, evidence indicates that the sociocultural safety net provided by this traditional system of land use promotes natural resource management practices that overcome the "tragedy of the commons," which leads to land deforestation to increase cash crop production. In recognition of the benefits of dramatically reducing deforestation in Mexico and other developing countries, the World Bank and United Nations initiated two projects: the Forests and Climate Change Project (World Bank 2018) and REDD+, or the Reducing Emissions from Deforestation and Forest Degradation project (United Nations 2016). In May 2016, the World Bank reported that through job creation and other support to Ejidos and Indigenous communities, these programs have led to the conversion of 1.8 million ha of forestland to sustainable management, thus reducing Mexico's deforestation rates (World Bank 2018; United Nations 2016).

7.3.4 Impact of Energy Extraction and Production on Tribal Land Carbon Emissions

Within tribal lands, net carbon fluxes are estimated to be positive, with more carbon released to the atmosphere than is taken up in areas dominated by land leased for coal, oil, and gas extraction (primarily in the northern central United States and Canada). This is due to the carbon dioxide and methane (CH_4) released during extraction processes and the accompanying tree removal on forested lands. Fossil fuel extraction and uranium mining on tribal lands (described in the subsequent case studies) have resulted in significant ecosystem degradation and carbon emissions (Brugge et al., 2006). For tribal lands heavily vested in fossil fuel exploitation and use, carbon fluxes to the atmosphere may equal or even exceed those on similar non-tribal lands. Renewable energy generation on tribal lands primarily results from leasing lands or community-owned hydroelectric, geothermal, solar, wind, and biomass production facilities (U.S. DOE 2015).

Case Studies in Fossil Fuel and Uranium Extraction

The United States is a significant carbon emitter, and many of its fossil fuel resources are on tribal lands, where energy development is big business (Indigenous Environmental Network 2016; Mills 2016; Regan 2016). Fossil fuel and uranium extraction have provided economic gain for some tribes, but at the cost of significant environmental degradation, loss of cultural resources, and adverse health effects (Brugge 2006). Most of the low-sulfur coal mined in the United States is on tribal lands in the Southwest and Great Plains (Pendley and Kolstad 1980; NCAI 2015; U.S. EIA 2017a). The Osage tribe in Oklahoma and Crow Nation in Montana are pursuing coalbed CH_4 projects, while the Three Affiliated Tribes of the Fort Berthold reservation in North Dakota are entering the oil refinery business. The Southern Ute and Ute Mountain tribes in Colorado have developed their own oil business exploration and development companies and also have embraced coalbed CH_4 development. The Fort Mojave tribe along the lower Colorado River in Arizona and California is leasing its land to a California-based energy company, Calpine Corporation, to build a natural gas electrical generating plant. Easements allowing the building of electrical transmission lines throughout Indigenous lands are being negotiated, often without adequate input from grassroots tribal members.

Although nuclear energy production is carbon neutral, the human cost of nuclear fuels extraction has been high. The legacy of uranium mining and milling has resulted in considerable environmental and human health issues in Indigenous populations in the western United States, including the Navajo, Hopi, Southern Ute, Ute Mountain, Zuni, Laguna, Acoma, Eastern Shoshone, Northern Arapaho, and Spokane tribes. These legacy impacts are integral to the life cycle costs of nuclear energy production and should be included in assessments of nuclear energy's role in the carbon cycle. The largest open-pit uranium mine was located at Laguna Pueblo, New Mexico. Thousands of abandoned mining sites are

as yet unreclaimed, with 75% of unreclaimed mining sites occurring on tribal land (Moore-Nall 2015). Additional uranium milling locations are now "Superfund sites" (sites outlined in the U.S. Comprehensive Environmental Response, Compensation and Liability Act of 1980) on Navajo and Spokane tribal lands. Ecological destruction due to uranium mining and milling on tribal lands reduces the carbon-carrying capacity of these lands and impacts the ability of Indigenous communities to maintain traditional and sustainable land-use practices. The lack of compensation for human health impacts and continuing environmental problems resulting from uranium production led to the uranium mining ban on Navajo lands in the Diné Natural Resources Protection Act of 2005 (LaDuke 2005).

Case Studies in Renewable Energy Production

Renewable energy development on tribal lands is increasing (Jones 2014; Royster 2012) but is still limited by federal regulations, tribal land tenure, lack of energy transmission infrastructure on reservations, and economic challenges. Recent examples include a proposed solar facility on Hopi land near Flagstaff, Arizona, that would supply the town with electricity; two adjacent Navajo Nation solar projects near Kayenta, Arizona; and a Jemez Pueblo solar project in New Mexico (U.S. EIA 2017a). If these projects prove to be economically viable, increased interest and development of renewable energy resources on tribal lands may offset fossil fuel energy exploitation and consumption. One novel approach is the Tulalip Tribe's involvement in the Qualco anaerobic digester, which has been in operation since 2008. It utilizes animal waste, trap grease, and other pollutants (thus keeping them out of landfills and drains and preventing illegal dumping) and burns CH_4 to create renewable energy. This process helps clean the air and water, helps farmers keep their dairies operating, protects salmon streams, and provides environmentally friendly compost (Qualco Energy 2018).

7.4 Indicators, Trends, and Feedbacks

Ecological indicators, trends, and feedbacks for carbon cycle processes have not been monitored on tribal lands. As previously discussed, tribal communities that have adopted Eurocentric agricultural and land-use practices, such as raising cattle and growing irrigated crops, likely have land with carbon stocks and fluxes similar to those in neighboring non-tribal lands. In some cases, these stocks and fluxes could result in larger net carbon emissions to the atmosphere on tribal lands where reservation population pressures or adverse climatic conditions have increased land-use stresses. However, for other Indigenous lands, carbon stocks and fluxes may differ considerably from surrounding non-tribal areas because of more traditional and culturally distinct agricultural, forestry, and land-use practices. These practices include dryland farming, no-till seeding, in-ground soil composting, sustainable forest practices, and grazing management of open-range herds of bison and certain varieties of sheep.

Fossil fuel (e.g., oil, gas, and coal) extraction and uranium mining on tribal lands have produced significant ecological disturbances that affect carbon stocks and fluxes. Moreover, the carbon cycle impacts of fossil fuel extraction on tribal lands may exceed the impacts in non-tribal areas with active fossil energy economies when the accompanying ecological impacts are not addressed. In some cases, such as the abandoned uranium mines on Navajo Nation lands, the impacts of these disturbances were substantially greater compared to surrounding areas (Moore-Nall 2015).

Increased awareness of the value of Indigenous worldviews and traditional knowledge in sustaining landscapes that can effectively sequester carbon in soils and vegetation offers policymakers and resource managers insight into new approaches to carbon cycle management. Trends affecting carbon cycle processes in the future include 1) the cessation of uranium mining and decreases in fossil fuel extraction; 2) increasing on-reservation development and use of renewable energy; and

3) agricultural production adaptations increasingly based on traditional knowledge, which could include, but are not limited to, increasing reliance on traditional drought-resistant crops and agricultural practices and the local production of native foods.

7.5 Societal Drivers, Impacts, and Carbon Management

As previously described, carbon cycle issues are integral to natural resource and land management decision making by Indigenous communities across North America. Generational values rooted in deep connections to the Earth form the basis for many of these communities. Eurocentric agricultural practices and fossil fuel energy extraction challenge these values, especially when they promise opportunities for job creation and revenue generation for tribal communities facing extreme poverty, unemployment, and public health challenges. Inherent conflicts between traditional values and the need to improve community livelihoods underlie the societal drivers for land and natural resource management decisions that affect carbon management.

Current carbon cycle programs aiming to improve both land stewardship and economic development on tribal lands are constrained because of funding, education, governmental policies on agriculture pricing, and natural resource management, as well as limited federal government participation in global carbon markets. Indigenous communities share substantial socioeconomic challenges that make successful implementation of future carbon management programs dependent on revenue generation through sustainable management.

Drivers that can both positively and negatively affect carbon stocks and fluxes include:

- Increased population growth, increasing demand for water, and stresses from land use and limited natural resources in both tribal and surrounding non-tribal communities.
- Economic incentives for tribes to engage in fossil fuel extraction projects.
- Community stresses from high levels of poverty, unemployment, and public health issues.
- Strong cultural commitment to ecological stewardship among tribal members.
- Growing reliance on sustainable traditional agricultural and forestry practices and local native food production.
- Increased implementation of renewable energy projects on tribal lands for both local energy use and economic development.

7.6 Synthesis, Knowledge Gaps, and Outlook

As previously discussed, carbon inventories on native lands across North America are affected by the balance between the use of traditional practices and the economic drivers for more intensive agriculture and natural and energy resource exploitation. The extent to which traditional practices have been maintained or reintroduced serves as a guide for estimating carbon cycle impacts on tribal lands through comparisons to carbon cycle impacts on similar non-tribal land types.

Quantitative understanding of carbon stocks and fluxes on tribal lands is notably poor, with limited direct monitoring or modeling of carbon cycling. Nevertheless, carbon cycle issues are increasingly integral to natural resource and land management decision making, and they may be informed by further research involving partnerships to understand how traditional land-use practices alter the carbon cycle. Traditional Indigenous peoples' practices may offer new opportunities for carbon management. Further, because of the spatial extent of tribal lands and their potential to affect carbon cycling at large scales, an improved understanding of the carbon cycle on tribal lands would advance quantification of the continental carbon cycle. Many North American Indigenous communities maintain traditional practices that inherently affect carbon stocks and fluxes. These practices include sustainable management of forests, agriculture, and natural resources.

High levels of poverty and unemployment have encouraged some tribes with fossil fuel and mineral resources to engage in ecologically destructive extraction practices as a means to improve livelihoods. However, further development of renewable energy programs on tribal lands is providing new opportunities to improve reservation economies, community health, and carbon cycle sustainability.

7.6.1 Seven Generations Youth Education

Understanding the importance placed on youth education by Indigenous communities is critical to fostering and sustaining traditional practices of community and ecological sustainability that affect carbon management on tribal lands now and in the future. Tribal education is closely aligned with tribal core values and traditional concepts of sustainability and thus carbon cycle management (Tippeconnic III and Tippeconnic Fox 2012; Kimmerer 2002). In particular, youth are widely revered as representing the future vitality of tribal nations and tribal lands. This thinking is consistent with the core tribal value of sustainability, which often is articulated as planning for Seven Generations, that is, that the tribe's human, social, and natural capital must be sustained with a time horizon comparable to seven human life spans (Brookshire and Kaza 2013). Therefore, youth education, development, and leadership are near-universal tribal priorities, with tribal education being framed by traditional and cultural values and by deep connections to ancestral homelands (Cajete 1999). Tribal education is considered a journey and life pathway that is neither defined nor constrained by western notions of a segmented and stepwise educational pipeline. This approach has several practical implications. Tribal colleges and universities (TCUs) were created, in large part, to provide a culturally relevant educational pathway that is congruent with core tribal values, traditions, and commitments to sustainability (Benham and Stein 2003). TCUs often serve as the research and science centers for tribal nations, conducting primary research on tribal issues, maintaining repositories of cultural and natural assets, and facilitating long-term tribal planning on issues such as climate change and sustainability, economic development, and health and wellness. TCUs exemplify the Seven Generations approach by providing youth with the foundation, support, and pathway to become productive members of their tribal nation, thereby ensuring that the tribe and tribal lands will thrive into the future.

7.6.2 Knowledge Gaps and Ways Forward

Significant knowledge gaps remain in assessing the unique impacts of tribal land and resource management on carbon stocks and fluxes. Closing these gaps would benefit from the combined insight of native wisdom and western science about forest health, crop cultivation, livestock grazing, water management, ecosystem protection, and community health and well-being. These knowledge gaps should be discussed within the larger context and with a focus on ways to empower Indigenous communities and support their engagement in matters within their decision domains and spheres of influence that affect the carbon cycle. Research could usefully be directed at the unique circumstances and needs of Indigenous communities. Particular research needs include:

- Quantifying the impacts of traditional practices on carbon stocks and fluxes, including the use of fire on the landscape, co-cropping of synergistic plants, and cultivation of plants with high moisture retention and temperature tolerance.
- Evaluating potential changes in carbon fluxes from site-specific applications of carbon capture and sequestration efforts and developing quantification methods for projects involving soil enrichment and renewable energy.
- Evaluating opportunities for deploying innovative technologies and practices that potentially can affect carbon fluxes at the community level (e.g., renewable energy, energy-efficient substitutions, local sourcing, carbon-based purchasing policies, and carbon markets).

Actions that may contribute to future carbon storage and reduce carbon emissions on tribal lands include:

- Developing community-based programs that address carbon sequestration in the context of enhanced access to nutritional foods.
- Promoting intergovernmental coordination and cooperation among partners to preserve and protect the public trust, as well as the use of special relationships such as fiduciary obligations and consultation requirements and principles of free, prior, and informed consent (United Nations 2008).
- Advancing collaborative efforts to increase awareness and combine western science and traditional knowledge, including facilitation of access to and sharing of data, information, and expertise.
- Implementing place-based monitoring and systems for recording and reporting environmental observations to establish baselines and provide a history of changes in temperature, humidity, precipitation, phenology, and species compositions.
- Increasing knowledge sharing about traditional agricultural practices that minimize carbon emissions and enhance carbon storage.
- Engaging in outreach education about alternative, efficient, and economical energy production on tribal lands.
- Implementing programs that enable tribes to quantify and realize the economic benefits associated with sustainable forest management, reforestation, boreal forest protection, and sustainable agriculture.
- Building capacity among tribal youth to support and inform the next generation of decision makers.

Indigenous communities are continuing to create opportunities to locally develop more diverse, distributed, and sustainable sources of energy, food, and income, which is strengthening ecological and community resilience and enhancing sustainable carbon management.

SUPPORTING EVIDENCE

KEY FINDING 1

Many Indigenous peoples in North America follow traditional agricultural and land-use practices that govern carbon cycling on tribal lands. These practices include no-till farming; moving domesticated animals seasonally in accordance with forage availability; growing legumes and cover crops; raising crops and livestock native to ancestral landscapes; and managing forests sustainably with fire, harvest, and multispecies protection.

Description of evidence base

Key Finding 1 is supported by studies and detailed reports about Indigenous tribes (e.g., AANDC 2013; Assies 2007; Chief et al., 2016; NCAI 2015; Tiller 1995) and agricultural crop and grazing and forestry practices (Zomer et al., 2017; Baker et al., 2007; Redsteer et al., 2010; Drinkwater et al., 1998; Gabriel et al., 2006; CSKT 2000; Bennet et al., 2014).

Major uncertainties

Uncertainties result from the limited number of reports in the literature documenting the extent to which traditional practices on native lands have impacted carbon cycle processes.

KEY FINDING 2

Scientific data and peer-reviewed publications pertaining to carbon stocks and fluxes on Indigenous (native) lands in North America are virtually nonexistent, which makes establishing accurate baselines for carbon cycle processes problematic. The extent to which traditional practices have been maintained or reintroduced on native lands can serve as a guide for estimating carbon cycle impacts on tribal lands by comparisons with practices on similar non-tribal lands.

Description of evidence base

Key Finding 2 is supported by findings presented in the *First State of the Carbon Cycle Report* (CCSP 2007) and resources on carbon programs in the United States (NICC 2015), deforestation in Mexico (Deininger and Minten 1999), and the First Nations Carbon Collaborative in Canada (IISD 2010, 2011).

Major uncertainties

Uncertainties result from a lack of in-depth studies and technical reports documenting carbon stocks and fluxes on tribal lands throughout North America.

KEY FINDING 3

Fossil fuel and uranium energy resources beneath tribal lands in the United States and Canada are substantial, comprising, in the United States, 30% of coal reserves west of the Mississippi River, 50% of potential uranium reserves, and 20% of known oil and gas reserves, together worth nearly $1.5 trillion. Fossil fuel extraction and uranium mining on native lands have resulted in emissions of carbon dioxide and methane during extraction and fuel burning. Energy resource extraction on tribal lands also has resulted in substantial ecosystem degradation and deforestation, further contributing to carbon emissions.

Description of evidence base

Key Finding 3 is supported by resources on fossil fuel and uranium extraction on tribal lands (Indigenous Environmental Network 2016; Mills 2016; Regan 2014, 2016; U.S. EIA 2017a, 2017b; Grogan 2011; U.S. EPA 2018; Moore-Nall 2015) and on ecological degradation from energy extraction (Brugge and Goble 2002; Diep 2010).

Major uncertainties

Uncertainties result from the lack of carbon emissions monitoring during energy extraction on tribal lands. Although energy extraction and use on Native American and First Nation lands are fairly well documented, carbon emission and consumption measurements are scarce, and studies of the adverse effects of tribal fossil fuel economies are limited.

KEY FINDING 4

Renewable energy development on tribal lands is increasing but is limited by federal regulations, tribal land tenure, lack of energy transmission infrastructure on reservations, and economic challenges.

Description of evidence base

Key Finding 4 is supported by reports on the opportunities and challenges for renewable energy production on tribal lands in the United States (Saugee 2012; Anderson 2005; Bronin 2012; U.S EIA 2017a, 2017b; Jones 2014; Royster 2012; Canada Energy and Mines Ministers' Conference 2016; Natural Resources Canada 2016a; Notzke 1994].

Major uncertainties

Uncertainties result from a limited number of case studies of areas where renewable energy sources have been developed and operated on tribal lands for extended periods of time.

KEY FINDING 5

Colonial practices of relocation, termination, assimilation, and natural resource exploitation on native lands have historically hindered the ability of Indigenous communities to manage or influence land-use and carbon management both on and off tribal lands. These factors combined with contemporary socioeconomic challenges continue to impact Indigenous carbon management decision making.

Description of evidence base

Key Finding 5 is supported by reports on climate vulnerability of Indigenous peoples (Bennet et al., 2014; Melillo et al., 2014) and the impacts of European settlement on tribal communities (NCAI 2015; GAO 2015; Indigenous Environmental Network 2016; Mills 2016; Regan 2016; Royster 2012; Statistics Canada 2011; Cultural Survival 1999; Minority Rights Group International 2017).

Major uncertainties

Uncertainties result from the limited number and duration of carbon cycle education programs implemented in North America and globally.

KEY FINDING 6

The importance placed on youth education by Indigenous communities creates opportunities for future generations to sustain and pass on traditional knowledge important to managing carbon stocks and fluxes on native lands.

Description of evidence base

Key Finding 6 is supported by reports on the tribal community youth education programs in the United States (Tippeconnic III and Tippeconnic Fox 2012; Kimmerer 2002; Cajete 1999; Brookshire and Kaza 2013).

Major uncertainties

Uncertainties result from the limited number of comprehensive studies on the role youth education plays in sustaining traditional practices for different Indigenous groups in Mexico and Canada, as well as uncertainty in the magnitude to which those practices could affect the carbon cycle.

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Appendix 7A
Summary Descriptions of Indigenous Communities in North America

7A.1 Location and Populations

According to the 2010 Census, the United States is home to 5.2 million people of American Indian or Alaskan Native heritage. Together, they comprise the 567 federally recognized tribes, 229 of which are in Alaska and the remaining 338 in 34 other states (NCAI 2015; U.S. Census Briefs 2012). About 41 million hectares (ha) are under American Indian or Alaskan Native control, with approximately 5.2 million people identified as American Indian/Alaskan Native (alone or in combination with other races). Approximately 22% of Native Americans live on tribal lands and 78% live in urban or suburban environments, with 19.5% of Native people living in Alaska (Norris et al., 2012).

Most American Indians and Alaskan Natives live in the western United States (40.7%), followed by the South (32.8%), Midwest (16.8%), and Northeast (9.7%; Norris et al., 2012). States with the highest populations of Native Americans living on or near tribal reservations are Oklahoma (471,738), California (281,374), and Arizona (234,891; BIA 2013). The largest reservation in the United States is the Navajo Nation Reservation of Arizona, New Mexico, and Utah (about 7 million ha), with a population of 169,321. The second most populated reservation is Pine Ridge Reservation in South Dakota and Nebraska, with 16,906 Native Americans (Norris et al., 2012).

According to the 2011 National Household Survey, Canada is home to 851,560 First Nation people that collectively comprise more than 600 First Nation and Indian bands. Of these, most live in Ontario and the western provinces. For example, about 23.6% of Canada's First Nation people live in Ontario (201,100), 18.2% in British Columbia (155,020), and 13.7% in Alberta (116,670; Statistics Canada 2011). First Nation people make up about one-third of the total population in the Northwest Territories and one-fifth of the population in the Yukon. Of the 851,560 people who self-identify as First Nations, 637,660 are officially registered under Canada's Indian Act. Nearly half of those registered (49.3%, or 316,000) live on reserves or Indian settlements (Statistics Canada 2011).

Mexico's Indigenous community consists of 16.9 million people, the largest such community in North America. These people represent 15.1% of the national population and together speak 68 Indigenous languages and 364 dialects (Del Val et al., 2016). Although Mexico does not have a system of reserves or reservations for Indigenous people, the majority (80%) of all people who speak an Indigenous language live in the southern and south-central regions of Mexico (Cultural Survival 1999; Minority Rights Group International 2017). About 18.1% of Mexico's Indigenous people live in the state of Oaxaca, followed by Veracruz (13.5%), Chiapas (13%), Puebla (9.42%), Yucatán (8.2%), Hidalgo (5.7%), state of Mexico (5.6%), Guerrero (5.2%), San Luis Potosí (3.2%), and Michoacán (2.9%; (Cultural Survival 1999).

7A.2 Summary Descriptions by Geographical Region

7A.2.1 Native Americans in the United States

Alaskan Native

Alaska is home to only one federally designated reservation, and most Alaskan Natives are associated with village or regional "corporations" (created by the 1971 federal Alaska Native Claims Settlement Act). Many of the native communities

reside in coastal areas where commercial fishing and tourism are two major sources of income (Tiller 1995). Some of these communities face imminent relocation due to rising sea levels (Melillo et al., 2014).

Pacific Northwest

The Yakama Nation specializes in agricultural production across 57,500 ha of irrigated land and in forestry on 125,000 managed ha of timber. Fisheries along the Columbia River are primarily for subsistence and ceremonial use, and tourism supports other members of the tribe (Tiller 1995). Along the coast, the Quinault Indian Nation uses its reservation's resources primarily for fisheries, timber harvesting, and tourism related to trout and salmon fishing (Tiller 1995).

Southwest

The southwestern United States is home to some of the country's largest reservations, including the Navajo Nation (6,566,000 ha in Arizona, New Mexico, and Utah); Hopi (632,000 ha surrounded by the Navajo Nation in Arizona); and Tohono O'odham (1.1 million ha straddling the U.S.-Mexico border). Major industries and land uses on these reservations include mining of coal, oil, and natural gas and tourism in parks, monuments, and recreation areas (Tiller 1995). For other southwestern reservations, main industries and land uses are production agriculture and livestock (Gila River Indian Community in Arizona and Walker River Paiute Tribe in Nevada), fisheries (Pyramid Lake Paiute Tribe in Nevada), and mineral mining (Uintah and Ouray Reservation in Utah; Tiller 1995).

Intermountain West

The large Blackfeet, Flathead, and Crow reservations in Montana contain rich farmland; extensive livestock grazing areas; commercial timberland; and coal, oil, and natural gas resources that, along with tourism, support the local economies. Land leases for energy extraction, hydroelectric power generation, and timber harvesting provide significant revenue streams for the tribes (Tiller 1995).

Great Plains

Some of the largest reservations in this region are in the Dakotas (e.g., Standing Rock, Cheyenne River, and Pine Ridge), where major industries and sources of tribal income include agriculture, oil and natural gas mining, forestry, and tourism (Tiller 1995).

Midwest

Most tribal reservations in the Midwest are in Michigan, Wisconsin, and Minnesota where timber harvesting, agriculture, big game hunting, fisheries, and tourism are major industries. In Wisconsin, the economy of the Menominee Indian Tribe revolves around sustainable forestry practices, with 95% of tribal lands forested after more than 100 years in the forestry industry (Tiller 1995). The Leech Lake Band of Ojibwa in Minnesota is the largest wild rice producer in the United States, with 4,000 ha of wild rice fields (Tiller 1995).

East Coast

Tribal reservations in the eastern United States are generally much smaller than those in the West because of European settlement, assimilation, and forced relocation. The Cherokee are the largest tribe in the United States, and their ancestral territory spanned over eight southeastern states. Most of the Cherokee Nation was forced to relocate to Oklahoma under an 1835 treaty. The Eastern Band of the Cherokee, who resisted removal during the 1800s, maintain a reservation in western North Carolina where tourism is a major industry and some commercial revenues are produced from small-scale farms and ranches. Tribes in the Northeast, such as the Allegany Reservation in New York, rely on agriculture, livestock, and some commercial forestry (Tiller 1995).

7A.2.2 First Nations of Canada

Eastern Canada: Quebec, Ontario, Newfoundland, and Labrador

In Canada's eastern woodlands region, First Nation tribes traditionally consisted of small groups (fewer than 400 people) who migrated in search of food, subsisting via hunting and trapping of migratory

animals. In fertile regions of southeastern Canada, the Iroquoian First Nations founded permanent communities where they farmed food crops, including corn, beans, and squash (AANDC 2013). Today, forestry provides opportunities for Indigenous people. In Newfoundland, Labrador, Quebec, and the Yukon, modern treaties have resulted in the transfer of more than 6 million ha to First Nation people. In Ontario, a 2014 to 2015 forest tenure modernization project provided funding to support sustainable forest licenses for Indigenous communities (Natural Resources Canada 2016a).

Central Canada: Alberta, Saskatchewan, and Manitoba

On the plains, First Nation people traditionally lived as migratory groups of hunters who followed the buffalo herds (AANDC 2013). Today, geothermal energy produced on the Peguis First Nation and Fisher River Cree Nation Reserve in Manitoba heats reserve homes, and First Nation people are trained and certified in geothermal trades (Paul 2015). On the remote Opaskwayak Cree First Nation reserve, where fresh produce is expensive, community members are experimenting with a method for indoor farming called "vertical farming" (CTV News 2016).

Western Canada: British Columbia

Along the Pacific Coast, First Nation people traditionally settled in permanent villages and subsisted on food resources from the ocean such as salmon, shellfish, sea lions, otters, whales, and seaweed. Red cedar from forests along the coast was used to build homes (AANDC 2013). Today, fisheries are an important industry for First Nations located in western Canada, where salmon, halibut, herring, and other fish are caught and processed in canneries (Notzke 1994). Forestry is also an important industry in this region. The First Nations Forestry Council of British Columbia works to support First Nation forestry activities through training programs, business support, policy development, mountain pine beetle action plans, ecosystem stewardship planning, and more (B.C. First Nations Forestry Council 2015). In central British Columbia, a liquid natural gas pipeline called Pacific Northwest LNG is under development. For environmental reasons, some First Nation groups oppose the pipeline while others support it for the economic benefits it will bring their First Nation communities (Jang 2016).

The Far North: Yukon and Northwest Territories

First Nation people of northwestern Canada traditionally hunted for game animals such as caribou across large territories (AANDC 2013). Today, the Yukon and Northwest territories are used for renewable and nonrenewable energy projects such as crude oil, natural gas, thermal electrical facilities, hydroelectric plants, and wind energy projects. Several pipelines carry crude oil and natural gas through the region (Canada National Energy Board 2011). Some First Nation people oppose energy development projects. For example, in the Yukon Territory, members of the Vuntut Gwitchin First Nation live along the migration route of the Porcupine caribou herd and rely on resources provided by the herd for food, clothing, and crafts. Their traditional way of life is being threatened by oil and gas companies that want to develop the Arctic National Wildlife Refuge (Vuntut Gwitchin First Nation, N.D.).

7A.2.3 Indigenous Communities in Mexico

Oaxaca and Guerrero

In the La Mixteca region of Mexico, which covers portions of the states of Oaxaca, Puebla, and Guerrero, centuries of destructive land-use practices have converted forest into desert. Here, Mixteca Indian farmers are reviving pre-Hispanic farming practices to restore and farm the land. Actions taken by these farmers include terracing hillsides, plowing with oxen, and farming via a technique called "milpa," where corn, squash, and beans grow together and increase soil nutrients (Malkin 2008).

Yucatán Peninsula and Quintana Roo

In Quintana Roo, forest resources provide a major source of income for the Mayan people, who make up about 25% of the population (Bray et al., 1993). Traditionally, the Maya used the forest for non-timber products such as palms for roof thatching,

fruits and herbs for food and medicine, and deer and peccary for meat. In the 1970s, the Maya and members of local Ejidos (communally farmed lands) began to harvest trees for railroad ties. In the 1980s, a forestry pilot program helped members of the Ejidos learn timber marketing strategies and sustainable management techniques. The Ejidos of central Quintana Roo occupy more than 400,000 ha of forest, much of which is permanent forest reserve (Bray et al., 1993).

Sierra Madre Occidental (Jalisco, Nayarit, Zacatecas, and Durango)

In the Sierra Madre Occidental Mountains, Huichol people live as subsistence farmers, using slash-and-burn practices to convert forest into agricultural land. They produce mostly maize, but also beans, squash, and sometimes livestock. Some Huichol are cattle ranchers, and others sell lumber. The quality of Huichol land is harmed by the slash-and-burn farming, and cattle grazing further damaged soil quality (Cultural Survival 1992).

Central Highlands, Sierra Norte de Puebla, and the Gulf Coast

The Nahua, speakers of the Nahuatl language, live near what was once the center of the Aztec empire. Most Nahua farm, growing maize, beans, chili peppers, squash, camotes, onions, tomatoes, and other cash crops such as sugarcane and coffee. Most families supplement farming with other sources of income (Sandstrom 2008).

7A.3 Land Tenure and Water Rights

U.S. reservation lands not "allotted" to individual tribal members under laws enacted in the late 1800s and early 1900s are held "in trust" by the U.S. government, meaning that the federal government must manage the lands and resources in a manner most beneficial to tribes (NCAI 2016). While tribal governments have the authority to manage their land base, the complexities of overlapping jurisdictions and land-use customs can delay crucial resource management decisions. For this reason, tribally owned lands may face greater obstacles to achieving sustainable resource management than public or private lands (Anderson and Parker 2008; Russ and Stratman 2013).

Land-tenure issues create challenges for tribal communities managing natural resources on reservation lands. Some reservations consist entirely of trust land, but, as a result of the General Allotment Act of 1887, many reservations also include other types of land, such as land owned by individual Indian families or land owned by non-Indigenous people who acquired the land from tribal families (Frantz 1999). The resulting checkerboard pattern of land ownership on many reservations is problematic for farming, ranching, and other activities—including developing and implementing carbon management plans—that require access to or management of large land tracts (Indian Land Tenure Foundation 2016). On trust lands, approval by the U.S. Secretary of the Interior is required for most land-use decisions, complicating tribes' ability, for example, to sell, lease, or develop their lands (Indian Land Tenure Foundation 2016).

In addition to land-tenure issues, Native American tribes in the United States have historically faced challenges in obtaining water for their reservations (Colby et al., 2005; McCool 2002; Thorson et al., 2006). In arid regions of the West, early settlers began a tradition of removing water from rivers via dams, diversions, and canals for agriculture, mining, and other purposes. Native American reservations downstream from western civilizations had no guarantee of sufficient water delivery during much of the 1800s. A 1908 Supreme Court decision known as the Winters Doctrine set the priority use date for water rights on tribal reservations as the same date that each reservation was established regardless of whether the tribe was using water for irrigation or other purposes at that time (Frantz 1999). The Winters Doctrine means that, today, tribes hold some of the most senior (highest-priority) water rights (referred to as "paper water") on river systems in the West. However, gaining access to actual water allocations ("wet water") can still be a long and arduous process for tribes that involves legal settlements

or adjudication agreements with federal and state governments.

On Canadian First Nation reserves, land is held in trust by the crown for use by specific bands. A "First Nation band" (or First Nation) is a recognized self-governing Indigenous community under the Indian Act of 1876 (Canada Indian Act 1985). The Canadian government may assign individual Indians the right to use land via certificates of possession (CP), but they do not have full legal ownership. Land not assigned by CP to an individual is held as community property of the band. Although bands may not sell reserve land, they may lease it to non-Indigenous people for uses such as natural resource development, farming, ranching, recreation, or rights-of-way for transportation or transmission (McCue 2011). Canadian First Nation tribes face land-tenure challenges similar to those confronting many Native Americans in the United States. Land-use opportunities may be limited by a reserve's location (e.g., areas with limited economic opportunities) or resource scarcity. Governmental regulations on access to fish, timber, mineral, subsurface, and other resources may restrict band members' efforts to develop land. In addition, reserve lands often are intersected by government rights-of-way for power lines, railroads, and highways, dividing useable spaces and making land use more difficult (Hanson 2009).

Water rights laws differ by province across Canada and consist of either prior allocation, public authority, riparian rights, or civil code. In addition, Indigenous and Canadian water rights laws co-exist. Prior to colonization, Indigenous cultures governed water use via their own customs and practices. The Constitution Act of 1982 protects any Indigenous rights (including water) not taken away from First Nations by 1982 (Canada Program on Water Governance 2010).

Unlike the United States and Canada, Mexico does not have a system of federal reserves or reservations. Rather than setting aside land and resources for Indigenous people, the Mexican government historically focused on cultural integration via assimilation (Minority Rights Group International 2017). Today, Mexico's constitution guarantees Indigenous people the right to self-determination, including the right to autonomy, education, infrastructure, and freedom from discrimination (Aban 2015). Each state has its own constitution, and some states have established legislation that limits the rights recognized by the national constitution (OHCHR 2011). Rights of Indigenous people vary from state to state; in Chiapas, Michoacán, and Oaxaca, Indigenous people have formed autonomous Indigenous governments (Minority Rights Group International 2017).

Section III

STATE OF AIR, LAND, AND WATER

These chapters present carbon cycle fluxes and processes in different physical and ecological domains, including the atmosphere, soils, inland and coastal waters, and the coastal ocean, as well as in terrestrial ecosystems such as forests, grasslands, and those in Arctic regions. Understanding these ecosystems is fundamental to assessing and predicting net carbon sources and sinks, including feedbacks to and from the climate system. These ecosystems also represent key carbon reservoirs with sensitivity to changes in climate and atmospheric composition.

Chapter 8
Observations of Atmospheric Carbon Dioxide and Methane

Chapter 9
Forests

Chapter 10
Grasslands

Chapter 11
Arctic and Boreal Carbon

Chapter 12
Soils

Chapter 13
Terrestrial Wetlands

Chapter 14
Inland Waters

Chapter 15
Tidal Wetlands and Estuaries

Chapter 16
Coastal Ocean and Continental Shelves

8 Observations of Atmospheric Carbon Dioxide and Methane

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KEY FINDINGS

1. Global concentrations of carbon dioxide (CO_2) and methane (CH_4) have increased almost linearly since the *First State of the Carbon Cycle Report* (CCSP 2007; see Figure 8.1, p. 339). Over the period 2004 to 2013, global growth rates estimated from the National Oceanic and Atmospheric Administration's marine boundary layer network average 2.0 ± 0.1 parts per million (ppm) per year for CO_2 and 3.8 ± 0.5 parts per billion (ppb) per year for CH_4. Global mean CO_2 abundance as of 2013 was 395 ppm (compared to preindustrial levels of about 280 ppm), and CH_4 stands at more than 1,810 ppb (compared to preindustrial levels of about 720 ppb) (*very high confidence*).

2. Inverse model analyses of atmospheric CO_2 data suggest substantial interannual variability in net carbon uptake over North America. Over the period 2004 to 2013, North American fossil fuel emissions from inventories average 1,774 ± 24 teragrams of carbon (Tg C) per year, partially offset by the land carbon sink of 699 ± 82 Tg C per year. Additionally, inversion models suggest a trend toward an increasing sink during the period 2004 to 2013. These results contrast with the U.S. land sink estimates reported to the United Nations Framework Convention on Climate Change, which are smaller and show very little trend or interannual variability.

3. During most of the study period covered by the *Second State of the Carbon Cycle Report* (2004 to 2012), inverse model analyses of atmospheric CH_4 data show minimal interannual variability in emissions and no robust evidence of trends in either temperate or boreal regions. The absence of a trend in North American CH_4 emissions contrasts starkly with global emissions, which show significant growth since 2007. Methane emissions for North America over the period 2004 to 2009 estimated from six inverse models average 66 ± 2 Tg CH_4 per year. Over the same period, CH_4 emissions reported by the U.S. Environmental Protection Agency equate to a climate impact of 13% of CO_2 emissions, given a 100-year time horizon.

Note: Confidence levels are provided as appropriate for quantitative, but not qualitative, Key Findings and statements.

8.1 Introduction

Atmospheric carbon dioxide (CO_2) and methane (CH_4) are the primary contributors to anthropogenic radiative forcing. Atmospheric concentration measurements of these two species provide fundamental constraints on sources and sinks, quantities that need to be monitored and understood in order to guide societal responses to climate change. These atmospheric observations also have provided critical insights into the global carbon cycle and carbon stocks and flows among major reservoirs on land and in the ocean. This chapter discusses atmospheric CO_2 and CH_4 measurements and their use in inverse modeling.

After decades of steady growth in anthropogenic carbon emissions associated with fossil fuel consumption, global emissions began to stabilize in 2014 and 2015 (BP 2016). Global emissions nearly doubled from 5,000 teragrams of carbon (Tg C) per year in 1980 to around 10,000 Tg C per year in 2015. In North America, emissions recently have been decreasing: in Canada from 151 to 141 Tg C per year between 2004 to 2013, and in the United States from 1,570 to 1,407 Tg C per year over the same time period (Boden et al., 2017). Nevertheless, the global atmospheric CO_2 concentration has passed the 400 parts per million (ppm) milestone (a part per million represents the mole fraction of CO_2 in dry air and is equivalently expressed as μmol per mol). Given the long lifetime of atmospheric CO_2, this global burden will continue to rise as long as net emissions remain positive.

The global atmospheric growth rate of CO_2 has averaged around half the rate of CO_2 input from fossil fuel combustion over the last 50 years, rising

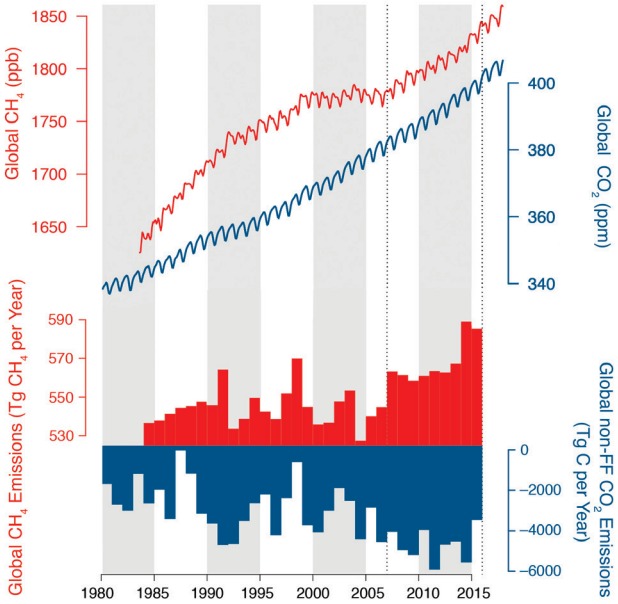

Figure 8.1. Global Monthly Mean Concentrations of Methane (CH_4; red line) and Carbon Dioxide (CO_2; blue line) and Global Annual Emissions of CH_4 (red bars) and Nonfossil Fuel Annual Emissions of CO_2 (blue bars). Global CH_4 and CO_2 concentrations (in parts per billion [ppb] and parts per million [ppm], respectively) are from the National Oceanic and Atmospheric Administration's Marine Boundary Layer product. Methane emissions were generated from annual growth rates of marine boundary layer CH_4, assuming a CH_4 lifetime of 9.1 years. Carbon dioxide emissions were generated from annual growth rates of marine boundary layer CO_2, converted to emissions using a factor of 2,128 teragrams of carbon (Tg C) per year per ppm and removing anthropogenic fossil fuel emissions. From 1980 to 2016, these global fossil fuel emissions grew steadily from about 5,000 Tg C per year to about 9,200 Tg C per year (Boden et al., 2017). Dotted vertical lines in 2007 and 2016 represent approximate reference times for publication of the first and second *State of the Carbon Cycle* reports.

from less than 1 ppm per year in the early 1960s to around 2.5 ppm per year between 2010 and 2015 (see Figure 8.1, this page; Ballantyne et al., 2015). Although the growth rate varies substantially from year to year, mainly in response to the El Niño–Southern Oscillation (Bacastow 1976; Sarmiento et al., 2010), the trend in net CO_2 absorption by the terrestrial biosphere and the ocean has increased from around 2,000 Tg C per year in 1960 to nearly 5,000 Tg C per year in 2015 (see Figure 8.1, this page; Ballantyne et al., 2015). Although the total sink is well constrained, now limited mainly by the ~5% to 10% uncertainty on global fossil fuel emissions, its partitioning between land and ocean and on land between continents is still uncertain. Accordingly, there is no consensus on the fraction of the global sink in North America, although almost all inventory, biospheric model, and atmospheric studies show it to be a sink (King et al., 2015).

The global abundance of CH_4 grew significantly from 1984 to 1996, but between 1997 and 2006 there was no significant change in global burden (see Figure 8.1, this page). This quasi-asymptotic behavior can be explained as an approach to steady-state concentrations (Dlugokencky et al., 1998). The balance between surface sources and atmospheric chemical loss, which is mainly due to oxidation by hydroxyl radicals, can be explained by constant emissions and a constant atmospheric CH_4 lifetime. For the emissions calculations reported in this chapter, a value of 9.1 years was used for this lifetime (Montzka et al., 2011). Indeed, global net emissions exhibited variability but no significant trend between 1984 and 2006 (Dlugokencky et al., 2011; see Figure 8.1, this page). After 2007, however, global CH_4 abundance began to rise rapidly (e.g., Dlugokencky et al., 2009; Nisbet et al., 2016), implying an increase in global emissions from 541 ± 8 Tg CH_4 per year (1999 to 2006) to 569 ± 12 Tg CH_4 per year (2008 to 2015). Emissions in 2014 and 2015 are particularly large, with a mean of 587 ± 3 Tg CH_4 per year. Analysis of trends in the ^{13}C:^{12}C content of CH_4 ($\delta^{13}C$) indicates that, at global scales, the rise since 2007 resulted predominantly from changes in microbial emissions (e.g., wetlands, livestock, and agriculture) and not fossil fuel–related emissions (Schaefer et al., 2016; Schwietzke et al., 2016). Moreover, because the recent CH_4 trend displays no significant meridional gradient, much of this new emissions increment likely originated in the tropics (Nisbet et al., 2016) and not in the northern midlatitudes.

Global total emissions of CO_2 and CH_4 are well constrained by available atmospheric measurements;

however, using these measurements to attribute to sources and sinks (e.g., fossil emissions versus terrestrial biosphere uptake) or partitioning between land and ocean regions remains difficult. In fact, even at smaller scales (i.e., continental regions as large as North America), substantial uncertainty remains about net contributions by terrestrial and aquatic ecosystems. The ability to use CO_2 and CH_4 time and space gradients to constrain North American sources and sinks is limited by current knowledge of atmospheric mixing and by the time and space density of calibrated observations (see Section 8.6, p. 349).

8.2 Historical Context

From the late 1950s through mid-1990s, measurements of atmospheric CO_2 and CH_4 concentrations were mostly targeted at understanding variations in "background" marine air, remote from the complex signals found over continents. Motivated largely by the finding of Tans et al. (1990) that Northern Hemisphere extratropical land regions were very likely a significant CO_2 sink, new attention was placed on understanding the role played by terrestrial ecosystems. New measurement sites were established on land, with an emphasis on platforms extending well into the daytime planetary boundary layer or higher, in an attempt to capture signals of regional (approximately 1,000 km) surface exchange (Gloor et al., 2001). This effort included observations on towers extending far above the ecosystem canopy (typically >300 m above ground level) and from light aircraft flying well into the free troposphere (typically >6 km above sea level).

The availability of calibrated, comparable observations of atmospheric CO_2 mole fractions on a common scale has made it possible to estimate surface exchange via inversion of atmospheric transport. Studies including Enting and Mansbridge (1991), Fan et al. (1998), and the ensuing Atmospheric Tracer Transport Model Intercomparison Project (TransCom) model intercomparisons (e.g., Baker et al., 2006; Gurney et al., 2002) reported widely ranging values of mean sinks for continental-scale land regions. These results demonstrated that, in the face of highly variable surface fluxes, uncertainties and biases in atmospheric transport models (e.g., Stephens et al., 2007), coupled with the sparseness of available observations, render the estimation of mean surface fluxes strongly underconstrained. In the context of a common estimation methodology, interannual variability in surface fluxes can be strikingly coherent between inversion models (Baker et al., 2006; Peylin et al., 2013), suggesting that standing biases in transport models may drive differences in the mean flux estimated by global inverse models.

At the time of the *First State of the Carbon Cycle Report* (SOCCR1; CCSP 2007), there was agreement within large uncertainty bounds between "bottom-up" estimates from terrestrial biomass inventories and "top-down" atmospheric studies (Pacala et al., 2001; see Ch. 2 and Ch. 3 in SOCCR1) on the size of the terrestrial CO_2 sink in North America. Atmospheric inverse modeling was discussed in SOCCR1, but the final fluxes reported for North America excluded estimates from those techniques. These estimates were brought together for the first time at the continental scale for the North American Carbon Program (NACP) interim regional synthesis project (Hayes et al., 2012; Huntzinger et al., 2012).

8.3 Current Understanding of Carbon Fluxes and Stocks

The global average atmospheric CO_2 concentration in 2015 of about 401 ppm (see Figure 8.1, p. 339) is roughly 20 ppm (5%) higher than in 2007. The anthropogenic excess of CO_2—the concentration in the atmosphere above the preindustrial level of about 280 ppm—has grown by 20% in just the 8 years since 2007. The 2015 global average concentration of CH_4 was about 1,833 parts per billion (ppb), which is 3% higher than in 2007 (a 5% increase in the anthropogenic excess).

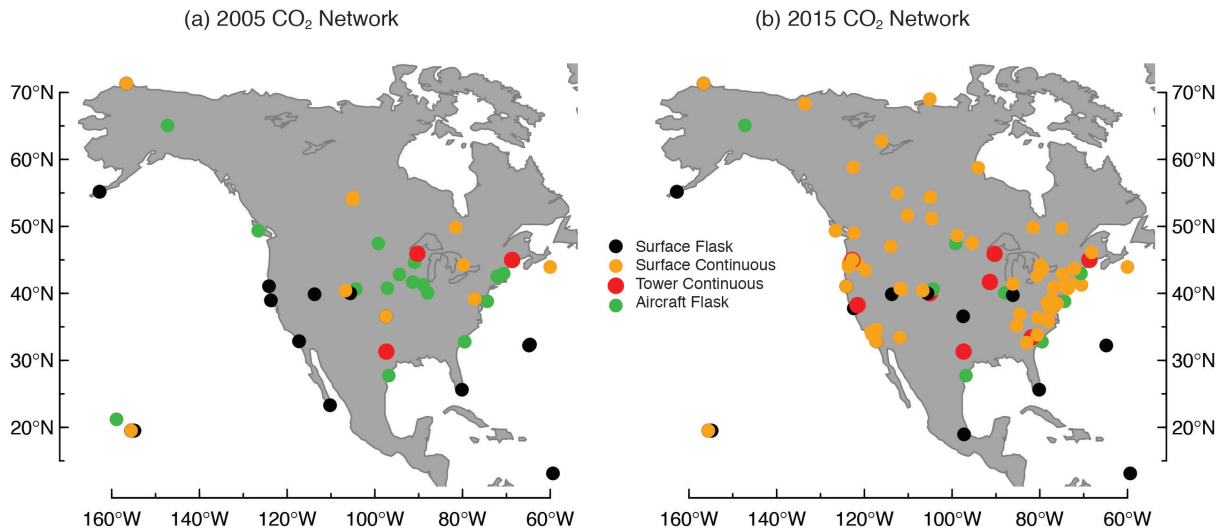

Figure 8.2. Growth of the North American Carbon Dioxide (CO_2) Monitoring Network from (a) 2005 to (b) 2015. Many National Oceanic and Atmospheric Administration aircraft sites were terminated after 2005. Unlike "surface" sites, "tower" sites generally have inlets 100 m to 400 m above the surface and sometimes sample air above the planetary boundary layer. About 90% of both tower and surface sites also report methane measurements.

8.3.1 Advances in Atmospheric Measurements and Platforms

Surface Networks

The observation network for atmospheric CO_2 and CH_4 has grown dramatically since SOCCR1 (see Figure 8.2, this page). Networks are now run by 1) governmental institutions such as the National Oceanic and Atmospheric Administration (NOAA), Environment and Climate Change Canada, U.S. Department of Energy, and California Air Resources Board; 2) research institutions including the National Center for Atmospheric Research (NCAR) and National Ecological Observatory Network (NEON); 3) universities such as Scripps Institution of Oceanography, The Pennsylvania State University, Oregon State University, and Red Universitaria de Observatorios Atmosfericos in Mexico; and 4) corporations (e.g., Earth Networks). Platforms and measurement techniques for observing greenhouse gas (GHG) distributions also have grown and become more diverse. In 2005, the North American CO_2 and CH_4 surface network mainly consisted of weekly surface flask–air sampling at a handful of sites and continuous observations at several observatories and three tall towers (see Figure 8.2, this page). Sustained records are now available from many more towers, especially those of intermediate (~ 100 m) height. As the density of the North American GHG measurement network has grown, the emissions sensitivity of observations has moved from hemispheric scales (using background marine boundary layer observations), to regional scales (using tower and aircraft observations), and, more recently, to local scales from urban networks and oil and gas measurement campaigns. These new *in situ* measurements of CO_2 and CH_4 (see Figure 8.2, this page) have been enabled by better availability of higher-precision, stable laser spectroscopic analyzers that require less-frequent calibration, although traceability to a common CO_2 reference scale is critical for this collection of networks to be unified. Currently, about 90% of the CO_2 network sites also report CH_4 measurements.

Remote Sensing

New remote-sensing approaches have emerged such as the international Total Carbon Column

Observing Network (TCCON), which now has six sites in North America among about 20 worldwide. TCCON measurements are made using high-resolution solar-tracking Fourier transform spectrometers (FTSs; Wunch et al., 2011), which are sensitive to the total CO_2 content of the atmospheric column, can provide constraints on large-scale carbon fluxes (Chevallier et al., 2011; Keppel-Aleks et al., 2012), and also help identify biases in satellite-based remote sensors (e.g., Wunch et al., 2016). Since SOCCR1, first-generation CO_2- and CH_4-dedicated near-infrared space-based spectrometers have been deployed aboard the Greenhouse Gases Observing Satellite (GOSAT; Japan Aerospace Exploration Agency) and the Orbiting Carbon Observatory-2 (OCO-2; National Aeronautics and Space Administration [NASA]) satellites. Numerous carbon cycle data assimilation systems are attempting to assimilate these CH_4 (GOSAT) and CO_2 (GOSAT and OCO-2) column averages to derive surface fluxes. These efforts are challenged by small but spatially and temporally coherent biases in the data (Basu et al., 2013; Feng et al., 2016; Lindqvist et al., 2015). Estimating emissions anomalies (as opposed to absolute emissions), such as carbon flux variability driven by climate events, has proved to be more successful (Basu et al., 2014; Guerlet et al., 2013; Reuter et al., 2014; Turner et al., 2017). Assimilating column-average GHG data from both ground- and space-based instruments into carbon cycle models is still a rather new activity that requires modifications in traditional atmospheric inverse models. They need to be modified to handle a much larger data volume, extract information from full-column averages, and assimilate retrievals contaminated by coherent biases, which can masquerade as atmospheric gradients arising from surface exchange.

Another remote-sensing approach for CO_2 uses light detection and ranging (LIDAR), which has been deployed at surface sites to measure the mean CO_2 along horizontal paths (Gibert et al., 2008, 2011) and aboard aircraft to measure partial-column integrals (Dobler et al., 2013). Space-based LIDAR total column CO_2 and CH_4 measurements are under development (Ehret et al., 2008), and a CH_4 system will be deployed on the MERLIN satellite sensor. LIDAR instruments have narrow beams and thus can often obtain data in partly cloudy regions that confound passive sensors. Because they are active, LIDAR instruments can obtain data in the absence of sunlight (at high latitudes or at night). Despite this appealing feature, LIDAR instruments are not yet broadly distributed for atmospheric research.

Vertical In Situ

Calibrated CO_2 and CH_4 total column values can be measured using *in situ* approaches. The AirCore is a thin steel tube that samples an air profile, typically during a balloon flight (Karion et al., 2010). Profiles (and thus column integrals) of CO_2 and CH_4 (Karion et al., 2010) extend to altitudes that allow sampling of nearly 99% of the atmospheric column of air. In addition to defining the vertical structure of CO_2 and CH_4 in both the troposphere and stratosphere, these data provide calibrated total columns that can be directly compared to remotely sensed soundings from space (e.g., OCO-2 and GOSAT) and the ground (TCCON). Time series of AirCore measurements are being established at Sodankylä, Finland; Orleans, France; Lamont, Oklahoma; and Boulder, Colorado. While not sampling the total column, *in situ* measurements taken aboard light aircraft flying between the surface and 6 to 8 km above sea level also are ongoing. These regular (biweekly to monthly) measurements capture the seasonal and interannual distribution of CO_2, CH_4, and other GHGs throughout North America (Sweeney et al., 2015; see Figure 8.2, p. 341). Although the number of air samples collected has not significantly increased since 2007, the number of gases measured has increased from eight to more than 50, including gases like carbonyl sulfide (COS) and the ^{14}C:C ratio of CO_2 ($\Delta^{14}CO_2$) that are tracers for biogenic and fossil fuel emissions.

Other Species

Carbon monoxide (CO) retrievals from the Measurements Of Pollution In The Troposphere (MOPITT) and Infrared Atmospheric Sounding Interferometer (IASI) satellite instruments have

been used to constrain biomass burning GHG emissions and help separate intact ecosystem carbon uptake from biomass burning emissions (e.g., van der Laan-Luijkx et al., 2015). Although CO retrievals from these platforms can be biased by 10% or more (De Wachter et al., 2012; Deeter et al., 2016; George et al., 2009), robust signals can still be gleaned since the variation in CO from large biomass burning events can be up to 500% of the background. While not a GHG measurement, solar-induced fluorescence (SIF), a direct by-product of photosynthesis, can be measured from space and is emerging as an important marker of terrestrial gross primary production (Frankenberg et al., 2011; Joiner et al., 2011) and complement to remotely sensed CO_2. Direct estimation of gross primary production from SIF retrievals remains an area of active research.

Process Tracers

Concentrations and isotopic ratios of carbon cycle process tracers such as COS, CO, $\Delta^{14}CO_2$, halogenated species, $^{13}CO_2$, $^{13}CH_4$, propane, and ethane are now being regularly analyzed in North American air and as part of the NOAA tower and aircraft networks and targeted regional and local measurement campaigns. These include programs such as the Mid-Continent Intensive (MCI; NACP) campaign, Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE; NASA), Atmospheric Carbon and Transfer-America (ACT-America) program (NASA), Indianapolis Flux Experiment (INFLUX), and Los Angeles megacities effort (see Section 8.3.2, this page). These process tracers allow for constraints on carbon cycle processes such as photosynthetic CO_2 fixation, fossil fuel emissions, and transport model fidelity.

8.3.2 Atmosphere-Based Fluxes from Local to Continental Scales

Short-Term and Regional to Local Emissions

Since SOCCR1 (CCSP 2007), studies of the carbon cycle have expanded to include regional campaigns designed to understand and quantify ecosystem and anthropogenic sources and sinks in particular regions and seasons. The NACP MCI campaign intensively sampled the atmosphere above the Midwest agricultural region during 2007 and 2008 and compared sources and sinks derived from atmospheric CO_2 data to those based on bottom-up inventories. The results showed a high degree of convergence between surface fluxes inferred from three atmospheric inversions and bottom-up inventories (Ogle et al., 2015; Schuh et al., 2013). CARVE studied boreal and Arctic ecosystem carbon cycling in Alaska using aircraft and tower CO_2 and CH_4 measurements between 2012 and 2015 (e.g., Chang et al., 2014). One significant finding was that an ensemble of process-based wetland emission models (Melton et al., 2013) systematically underestimated atmospherically constrained CH_4 emissions from tundra ecosystems on Alaska's North Slope (Miller et al., 2016). Recently launched regional studies also should provide new insights into North American carbon cycling. The ACT-America (2015 to 2019) program is designed to explore the structure of GHG distributions within synoptic weather systems and reduce atmospheric transport error in inverse flux estimates using a variety of aircraft observations. The new NASA CARbon Atmospheric Flux Experiment (CARAFE) airborne payload, which is designed for validation of regional carbon flux estimates, was recently deployed to collect airborne eddy covariance measurements for CO_2 and CH_4 (Wolfe et al., 2015). Other studies such as NASA's Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality (DISCOVER-AQ) and Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS), as well as the Texas Air Quality Study (TexAQS), have focused primarily on reactive gas compounds and air quality research but also have measured and interpreted CO_2 and CH_4 data (e.g., Brioude et al., 2012; Townsend-Small et al., 2016; Vay et al., 2011). At much larger scales, the HIAPER (High-Performance Instrumented Airborne Platform for Environmental Research) Pole-to-Pole Observations (HIPPO; 2009 to 2011) and the Atmospheric Tomography Mission (ATom; 2016 to 2018) projects have measured atmospheric trace gas species, including CO_2

and CH_4, along north-south transects in the Pacific and Atlantic oceans. These measurements are not significantly sensitive to North American emissions, but they are expected to help constrain large-scale carbon fluxes and atmospheric transport and, by extension, improve understanding of the North American carbon balance.

Many studies at more local scales have been designed to provide constraints on urban CH_4 and CO_2 emissions. A large global trend in urban migration is making cities loci of both emissions and their mitigation, thus driving interest in atmospheric measurement approaches to inform decision making (e.g., Duren and Miller 2012). There have been projects outside of North America (e.g., Bréon et al., 2015; Levin et al., 2011); some North American urban carbon balance studies include those in Indianapolis (INFLUX; Davis et al., 2017), Los Angeles (Feng et al., 2016; Wong et al., 2015; Wunch et al., 2009), Salt Lake City (McKain et al., 2012), and Boston (McKain et al., 2015). In general, these studies have deployed small networks of GHG sensors in and around cities and used the observed gradients, in conjunction with high-resolution atmospheric transport models and bottom-up inventories, to determine urban CH_4 and net CO_2 emissions (fossil and biogenic). Comparisons between atmospherically derived and bottom-up CO_2 emissions show varying degrees of agreement, even in the same city. In Indianapolis, a CO_2 flux calculation using tower observations and a high-resolution (1-km) atmospheric inversion system (Lauvaux et al., 2016) yielded emissions about 20% larger than either the Hestia Project (Gurney et al., 2012; Arizona State University) or Open-source Data Inventory for Anthropogenic CO_2 (ODIAC; Oda and Maksyutov 2011) inventory products, while aircraft mass-balance fluxes (Heimburger et al., 2017) were about 20% lower than the inventories. Indianapolis airborne mass balance CH_4 emissions were about 30% higher than a custom-made urban inventory, and the tower-based inversion suggested CH_4 emissions twice as large as the aircraft mass balance estimate. In Salt Lake City, another atmospheric inversion approach using high-resolution (1.3-km) meteorology also showed a high level of correspondence with the Vulcan Project. The California Research at the Nexus of Air Quality and Climate Change (CalNex) mission, which sampled CO_2 above Los Angeles, derived emissions 20% to 30% higher than ODIAC and Vulcan (Brioude et al., 2013; Gurney et al., 2012). In the Los Angeles megacities experiment and INFLUX, additional biogenic and anthropogenic process tracers like CO, $\Delta^{14}CO_2$, and numerous hydro- and halocarbons also have been measured (Newman et al., 2016; Turnbull et al., 2015). These data could enable partitioning the net CO_2 signals into anthropogenic and biogenic components.

Local studies also have been undertaken in and around oil and gas extraction fields. Between 2005 and 2016, U.S. natural gas extraction increased by over 38% (U.S. Energy Information Administration, www.eia.gov/dnav/ng/hist/n9010us2m.htm). The fraction of CH_4 that leaks during extraction and distribution is highly uncertain and is driving research on both bottom-up and top-down methods. Alvarez et al. (2012) estimated that if this CH_4 leak rate is greater than about 3%, the climate impact of natural gas combustion could equal or exceed that of coal on a per-unit energy basis. Some recent studies of CH_4 emissions from oil and gas production (e.g., Brandt et al., 2014) have found higher emissions compared to estimates from past U.S. Environmental Protection Agency (EPA) inventories. Field studies also have shown considerable variation among regions. For example, Karion et al. (2013) found that emissions from the Uintah Basin in Utah were about 9% of production, while Peischl et al. (2015) found leak rates well under 3% of production for the Haynesville, Fayetteville, and Marcellus shale regions. Based on a variety of studies at scales ranging from individual pieces of equipment to regional scales, Brandt et al. (2014) concluded that leakage rates are unlikely to be large enough to make the climate impact of natural gas as large as that of coal.

The answer to the question of why field studies suggest higher emissions than official inventories is likely related to the existence of a small number

of "super emitters" that are difficult to capture in inventory-based approaches, but whose atmospheric signatures are often seen in measurements (Brandt et al., 2014; Schwietzke et al., 2017; Kort et al., 2014). For example, Zavala-Araiza et al. (2015) found that half of CH_4 emissions from the Barnett Shale region were due to just 2% of oil and gas facilities, and the study achieved closure within error bounds between atmospheric methods and an inventory product derived from local emissions measurements. Although small in area and duration, these measurement campaigns have provided policy-relevant information using atmospheric CH_4 concentration data.

Interannual and Continental Emissions

Inverse models such as CarbonTracker have been continuously improved and upgraded to exploit the improved density of atmospheric CO_2 and CH_4 observations (Bruhwiler et al., 2014). Global inversions with regularly updated flux estimates include CarbonTracker (Peters et al., 2007; carbontracker.noaa.gov), the European Union's Copernicus Atmospheric Monitoring Service (CAMS; atmosphere.copernicus.eu; formerly MACC), Max Planck Institute Jena CarboScope project (Rödenbeck et al., 2003; www.bgc-jena.mpg.de/CarboScope), and CarbonTracker-Europe from Wageningen University (Peters et al., 2010; www.carbontracker.eu). These products constitute the ensemble of inverse models used in this chapter to estimate North American CO_2 fluxes.

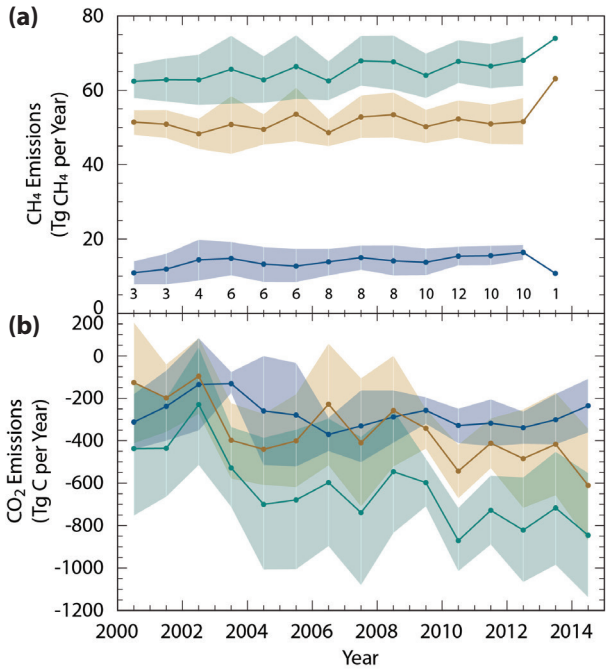

Figure 8.3. Inverse Model Estimates of Annual Emissions of (a) Methane (CH_4) and (b) Nonfossil Fuel Carbon Dioxide (CO_2) from 2000 to 2014. Estimates are given in teragrams (Tg) for North America (green), boreal North America (blue), and temperate North America (beige) based on the across-model mean of inverse models. Error bands represent one-sigma across-model spread taken as a proxy for model uncertainty. Methane emissions data are from the Global Carbon Project (GCP) inverse model collection of Saunois et al. (2016), with the number of models contributing to each annual mean shown in black. Carbon dioxide emissions are the across-model mean of the four inverse models collected for this report. Negative emissions represent a sink.

Mean annual CO_2 fluxes over North America from this ensemble are shown in Figure 8.3, this page, and listed in Table 8.1, p. 346. These inverse model flux estimates show some level of agreement about mean fluxes and patterns of interannual variability. However, they also manifest notable differences. These differences remain one of the most important indicators of the overall uncertainty in inverse model fluxes. The uncertainty in fluxes derived from inverse models has proven to be a difficult quantity to estimate directly, since those models depend on results from upstream analyses with complicated, unknown uncertainties. For instance, some of the overall difference in inverse model fluxes can be attributed to differing atmospheric transport among the models, which assume that the winds and diffusive mixing of the transport model are unbiased and subject only to random error. Another element of overall uncertainty comes from the structure of the flux estimation scheme in each inverse model. This structure includes the choice of prior emissions from the burning of fossil fuels, terrestrial biosphere, and the ocean used in the model. The interpretation of results from inverse models is further complicated by the fact that these

Table 8.1. Estimates of Annual, North American, Land Biosphere Carbon Dioxide (CO_2) Fluxes (Including Fire) Derived from Atmospheric CO_2 Measurements Using Inverse Models and the U.S. Environmental Protection Agency (EPA) Inventory over the Period 2004 to 2013

	CT2015	CAMS[a]	CTE2015	CarboScope[b]	Inverse Models	EPA	Fossil Fuel Emissions
Boreal North America	–160 ± 77	–356 ± 61	–302 ± 50	–407 ± 64	–306 ± 43		30 ± 1
Temperate North America	–352 ± 111	–602 ± 95	–252 ± 126	–365 ± 109	–393 ± 67	–202 ± 5[c]	1744 ± 37
North America	–511 ± 106	–959 ± 117	–555 ± 147	–773 ± 107	–699 ± 82		1774 ± 24

Emissions in teragrams of carbon (Tg C) per year are listed for the Atmospheric Tracer Transport Model Intercomparison Project's (TransCom) temperate and boreal North American regions (Gurney et al., 2002). The "inverse models" column averages across the four inverse models (CarbonTracker [CT], Copernicus Atmospheric Monitoring Service [CAMS], CarbonTracker-Europe [CTE], and CarboScope) and represents the best estimate from this ensemble. Fossil fuel emissions are derived from Boden et al. (2017). Values reported are the 2004 to 2013 mean plus or minus a measure of interannual and across-model variability (twice the standard error of the mean of annual emissions). Negative emissions represent a sink.

Notes

a) Version v15r4, atmosphere.copernicus.eu.

b) Version v3.8.

c) U.S. EPA (2017) estimates correspond to "managed lands" in the United States, which largely corresponds to the TransCom temperate North American region.

models retrieve spatiotemporal patterns of CO_2 and CH_4 fluxes that do not necessarily correspond with patterns expected from differing theories about ecosystem carbon exchange; therefore, they do not map directly onto improvements in process knowledge. Despite these limitations, inverse model results are important because their net carbon flux estimates are by construction consistent with atmospheric data constraints. Ensembles of inverse models using different transport, structure, data inputs, and priors are particularly useful since they mitigate some of these limitations.

Previous comparisons of inverse models such as Baker et al. (2006) and Peylin et al. (2013) indicated that, while each inversion manifests a different long-term mean flux estimate, the patterns of interannual variability tend to have better agreement. There is some indication of interannual variation coherence in the present collection of models, but with some significant disagreement, mainly from the Jena CarboScope model. Averaging across the inversions, the land biosphere sink in North America, including fire emissions, averaged over 2004 to 2013 is 699 ± 82 Tg C per year (mean ± two standard errors of the mean of the interannual and intermodel variability). This sink offsets about 39% of the fossil fuel emissions of 1,774 ± 24 Tg C per year for the same geographic area, although 98% of these anthropogenic emissions come from just the temperate North American region. Disagreement remains among these inversions about the average size of the North American sink, but they all estimate significant interannual variability in that sink. Over the temperate North American region, these inverse models estimate interannual variability (one sigma) of between 163 and 277 Tg C per year, equivalent to 45% to 83% of each model's mean flux.

The level of interannual variability from inverse models stands in stark contrast to the annual Inventory of U.S. Greenhouse Gas Emissions and Sinks, prepared by the U.S. EPA. EPA's U.S. GHG inventory estimates land use, land-use change, and

forestry (LULUCF) sector emissions on managed lands. Managed lands represent about 95% of total U.S. land cover and more than 99% of the conterminous United States, which corresponds well to the net biosphere fluxes estimated by inversion models for temperate North America. EPA's LULUCF CO_2 sink estimate has a 2004 to 2013 mean of 202 ± 5 Tg C per year (U.S. EPA 2017; mean plus or minus two standard errors of the mean). The small interannual variability in the EPA inventory of just 5 Tg C per year stands in contrast to all the inverse models. This low apparent variability may arise from the historical 5- to 14-year frequency at which U.S. Forest Service Forest Inventory and Analysis (FIA) plots have been resampled. Comparing the interannual variability of inventories and inversions is inherently difficult due to the mismatch in their temporal sensitivities.

Various estimates of North American surface CO_2 emissions were collected as part of the recent NACP regional interim synthesis (Hayes et al., 2012; Huntzinger et al., 2012) and REgional Carbon Cycle Assessment and Processes (RECCAP) effort (Canadell et al., 2011; King et al., 2015). The RECCAP North America study included a suite of inverse models collected by Peylin et al. (2013) with a 2000 to 2009 mean CO_2 sink of 890 ± 400 Tg C per year (mean and one sigma standard deviation), implying a larger sink than either inventory (270 Tg C per year) or terrestrial biosphere model (359 ± 111 Tg C per year) estimates (King et al., 2015). The current suite of inverse models collected for this report (see Table 8.1, p. 346) suggests North American biosphere emissions of 699 ± 82 Tg C per year averaged over 2000 to 2014. The models collected for this chapter also supplied results from their earlier versions to the RECCAP ensemble of Peylin et al. (2013). That report showed a wide range of North American flux estimates, but the subset of models used in this chapter all manifested sinks smaller than 500 Tg C per year for North America over the reporting period 2001 to 2004, whereas the other models all estimated greater sinks between about 500 and 1,500 Tg C per year.

The North American sink estimated from the suite of inverse models collected for this report agrees well with previous bottom-up estimates. SOCCR1 (Pacala et al., 2007) reported a sink of 666 ± 250 Tg C per year for 2003. This estimate was derived from bottom-up inventories and models and did not include information from atmospheric inverse models. Hayes et al. (2012) attempted to reconcile net biosphere emissions estimates from inventories, terrestrial biosphere models, and atmospheric inverse models averaged over 2000 to 2006 for North America. That study found a sink of 511 Tg C per year simulated by terrestrial biosphere models and an inventory-based sink estimate of 327 Tg C per year (with an estimate of additional noninventoried fluxes that brings the total sink estimate to 564 Tg C per year). The collection of inverse models used in that study manifested significantly larger sinks (981 Tg C per year) than the current collection. See Ch. 2: The North American Carbon Budget, p. 71, for an assessment of the overall agreement of these various estimates of North American surface CO_2 exchange with the atmosphere.

The use of regional models of CO_2 and CH_4 has become more common since SOCCR1. These models have focused, for example, on continental-scale processes (Butler et al., 2010; Gourdji et al., 2012; Schuh et al., 2010) or at the scale of the mid-continent (Lauvaux et al., 2012b; Schuh et al., 2013). Regional model CO_2 flux estimates for North America so far have been published for periods of up to 1 year, with multi-year analyses only available from global inversion approaches. One prominent result from regional inverse CO_2 studies is the sensitivity of the annual net CO_2 flux to defining the inflow of atmospheric CO_2 into the study region (Gourdji et al., 2012; Schuh et al., 2010). Lauvaux et al. (2012b) demonstrated that this sensitivity could be minimized with observations at the inflow boundaries. This finding highlights the importance of global-scale measurement networks and carbon reanalysis systems for understanding North American carbon fluxes. More recently, CH_4 has received more attention with regional inversions for the continent (Kort et al.,

2008; Miller et al., 2013), California (Jeong et al., 2013), and Alaska (Chang et al., 2014; Miller et al., 2016). Additional uncertainties in inverse modeling approaches arise from sparse data coverage. When the observational network is not strongly sensitive to particular land regions, inverse modeling systems must make assumptions about spatial and temporal patterns of emissions. As with the issue of boundary inflow, mitigating this sensitivity necessitates building a denser, intercalibrated measurement network.

8.4 Indicators, Trends, and Feedbacks

Atmospheric CH_4 and CO_2 levels continue to increase. In the case of CO_2, this increase is unambiguously a result of anthropogenic emissions, primarily from fossil fuel combustion, with North America accounting for about 20% of global emissions. The recent rise in global CH_4 concentrations (see Figure 8.1, p. 339), on the other hand, has been attributed primarily to biological, not fossil, processes on the basis of a concomitant decrease in the global mean ^{13}C:^{12}C ratio and the tropical origin of the increase (Nisbet et al., 2016; Schaefer et al., 2016; Schwietzke et al., 2016). Two recent analyses render the causes of recent CH_4 growth rate changes less clear. First, studies have pointed out that the tropospheric CH_4 sink may not have been constant over recent years as had been assumed (Rigby et al., 2017; Turner et al., 2017). Secondly, Worden et al. (2017) suggest that atmospheric $\delta^{13}C$ of CH_4 may have decreased because of less biomass burning, thus allowing for an increase in isotopically heavier fossil fuel CH_4 sources. Nonetheless, these results mostly pertain to the global mean and do not directly bear on potential trends in North American emissions. Despite the recent increase in oil and gas production due to new extraction technologies, both inventories and atmospheric inversions do not reveal an increase in North American CH_4 emissions (Bruhwiler et al., 2014; Miller et al., 2013; U.S. EPA 2016; see Figure 8.3, p. 345). Normalizing CH_4 and CO_2 emissions using a 100-year global warming potential (GWP) indicates that U.S. radiative forcing from CH_4 emissions from 2000 to 2013 equates to just 13% of that from CO_2. Changes in U.S., Canadian, and Mexican energy systems will affect the atmospheric trends of anthropogenic CO_2 and CH_4, but U.S. GHG emissions currently are dominated by CO_2 and are likely to remain so for the foreseeable future.

Much less certain than anthropogenic CO_2 sources is the balance of biogenic sources (respiration and fire) and sinks (photosynthesis). There is general agreement that the terrestrial biosphere of the United States, and North America as a whole, acts as a CO_2 sink (see Figure 8.3, p. 345, and Table 8.1, p. 346; Hayes et al., 2012; King et al., 2015), but there is substantial uncertainty about the location of and reasons for the sinks. There is evidence that their interannual variability is driven largely by climatic factors. For example, Peters et al. (2007) presented evidence for a direct effect of drought on the North American sink. Understanding the spatial and temporal variability of sinks is critical, because positive feedbacks between net ecosystem CO_2 exchange and climate represent a first-order uncertainty in climate projections (Bodman et al., 2013; Booth et al., 2012; Friedlingstein et al., 2006, 2014; Huntingford et al., 2009; Wenzel et al., 2014; Wieder et al., 2015). At hemispheric and global scales, atmospheric CO_2 data have proved to be a powerful constraint on the representation of the carbon cycle (including, to some measure, feedbacks) in climate models (e.g., Cox et al., 2013; Graven et al., 2013; Keppel-Aleks et al., 2013; Randerson et al., 2009). The present generation of global atmospheric inverse models is limited by the accuracy and resolution (generally about 1° × 1°) of meteorological transport, availability and accuracy of prior flux emissions, uncertainty about the spatial coherence of prior flux errors, and the limited set of observation sites shown in Figure 8.2, p. 341. Together, these limitations mean that, at present, global atmospheric inverse models cannot unambiguously resolve source-sink patterns below the scale of 5 to 10 million km^2. A new generation of regional and local models using much higher resolution meteorology (e.g., approaching the approximately 1- to 4-km resolution used by Lauvaux et al. [2016] and McKain et al. [2015]) will be more

capable of assimilating data from the sites in Figure 8.2, p. 341. Without quantitative knowledge of the spatial structure of flux uncertainties (Cooley et al., 2012; Ogle et al., 2015) and atmospheric transport errors (Díaz Isaac et al., 2014; Lauvaux and Davis 2014), these high-resolution inverse systems will have limited ability to determine the spatial structure of fluxes (Lauvaux et al., 2012a, 2016). Nonetheless, these improved inversion systems should enable better understanding of the climate-carbon relationship in North America.

8.5 Societal Drivers, Impacts, and Carbon Management

In a potential future when carbon emissions have a significant economic cost and international agreements to control emissions are in place, verifying claims of emissions mitigation and assessing the efficacy of mitigation strategies will be necessary. In addition to international agreements, 18 states have plans in place to reduce GHG emissions. Bottom-up methods based on economic, agricultural, and forest inventories provide much of the basis for these calculations. These methods are susceptible to systematic errors, including incomplete sectoral coverage, misreporting, and the use of uncertain emissions factors. Top-down methods derive emissions budgets consistent with atmospheric concentrations of GHGs, but they also contain systematic errors resulting from imperfect knowledge of atmospheric transport and lack of observations. Although these uncertainties place limits on the accuracy of top-down emissions estimates, atmospheric data still provide strong constraints on GHG emissions from local to global scales (e.g., Levin et al., 2010). As shown by the example of Brandt et al. (2014), natural gas super emitters can be localized from *in situ* observations even when they have not previously been identified by inventories. As described in this chapter, both existing and new technologies can provide independent and complementary information and help reconcile emissions estimates from the bottom-up and top-down approaches. From a carbon management and decision perspective, collecting and utilizing information from atmospheric data could provide additional information in regions and sectors where uncertainties in bottom-up inventories are large. Top-down emissions estimates can be produced with low latency and with robust uncertainty quantification. Together, these two methods can provide robust observational constraints on emissions at a variety of scales.

8.6 Synthesis, Knowledge Gaps, and Outlook

8.6.1 Findings from Atmospheric Inversions and Related Analyses

The present collection of atmospheric CO_2 inversions shows no clear trend in the boreal North American sink, but it does suggest the possibility of an increasing sink in temperate latitudes. A more robust feature of atmospheric inversions is that they show that the North American CO_2 sink is more highly variable and sensitive to drought and temperature stress than bottom-up biosphere models (King et al., 2015; Peters et al., 2007). Inversions also produce a larger mean sink and a deeper annual cycle than terrestrial biosphere models. Significant uncertainty remains about the magnitude of the mean North American carbon sink, in part because models disagree about the partitioning of the net sink between northern and tropical land regions. The mechanisms behind the land sink cannot be understood fully without more agreement on its location. Notably, distinguishing between a potentially short-lived sink due to recovery from past land-use practices (mainly a temperate Northern Hemisphere phenomenon) and a longer-term sink due to CO_2 fertilization remains elusive. Moreover, the role of carbon-climate feedback processes in North America, both negative (e.g., extended growing seasons and tree-line migration) and positive (e.g., permafrost carbon release and insect outbreaks), is poorly understood at present. Atmospheric measurements can impose significant constraints on these processes (e.g., Sweeney et al., 2015), and continued and expanded measurements, especially in sensitive Arctic and boreal regions, will be critical moving forward.

Inventories suggest that fossil fuel CO_2 emissions are stabilizing and even decreasing for certain

regions and sectors of the global and North American economy. This finding is difficult to verify given the *ad hoc* nature of the GHG observation network, lack of integration among programs, and sparse measurements of anthropogenic emissions tracers such as $\Delta^{14}CO_2$ and CO.

Individual atmospheric CH_4 inversions consistently show no trend and little interannual variability in total CH_4 emissions (natural and anthropogenic) for both the temperate (largely the United States) and boreal regions and the continent as a whole (see Figure 8.3, p. 345). These results suggest that North American emissions have not contributed significantly to the global upward trend that started in 2007. Increasing oil and gas production in North America could result in increased CH_4 emissions, a result apparently confirmed by Turner et al. (2016) on the basis of comparing inverse model estimates from different time periods. This conclusion has been called into question by Bruhwiler et al. (2017), who argue that robust trend detection is limited by interannual variability, the sparse *in situ* measurement network, and biased satellite CH_4 retrievals. Recent increases in atmospheric ethane and propane suggest increased CH_4 emissions from fossil fuel production, although there is uncertainty in this conclusion due to poorly quantified emissions ratios (Helmig et al., 2016). As with CO_2 though, little reliable spatial information is available from the current suite of CH_4 inverse models. This limitation hampers attribution to specific mechanisms including CH_4-climate feedbacks, especially in the boreal zone where permafrost degradation plays a key role in changing CH_4 and CO_2 fluxes (McGuire et al., 2016; see also Ch. 11: Arctic and Boreal Carbon, p. 428).

8.6.2 Future Atmospheric Measurement Challenges and Strategies for North America

Compatibility Among Networks

As the community expands research into new domains and with new measurement strategies, new challenges are emerging. Compatibility of measurements among existing and future networks is a concern, as there is ample history of calibration difficulties from the decades of *in situ* measurement experience (e.g., Brailsford et al., 2012). This challenge is being addressed by careful attention to calibration and participation in laboratory and field intercomparison activities (Masarie et al., 2011; www.esrl.noaa.gov/gmd/ccgg/wmorr/). Much more challenging is linking ground- and space-based remote-sensing measurements to each other and to the calibrated *in situ* networks. Concentrations derived from any remote-sensing gas measurement, whether ground- or space-based, cannot be formally calibrated because the measurement instrument cannot be "challenged" by a reference sample with a known concentration. Thus, identification and correction of biases remain a significant challenge. With the OCO-2 and GOSAT programs, the primary strategy has been to compare the satellite-based retrievals with TCCON retrievals. The TCCON retrievals of column CO_2 are themselves remote-sensing products that have been statistically linked to the World Meteorological Organization CO_2 calibration scale using aircraft *in situ* partial column CO_2 and CH_4 extrapolated to the top of the atmosphere (Wunch et al., 2011). This linkage remains uncertain due to the limited number of *in situ* profiles used and their limited maximum altitude. A limited number of nearly total column AirCore (Karion et al., 2010) measurements also have been compared with TCCON columns.

Bias correction of satellite retrievals remains challenging due to the limited number of TCCON stations (currently less than 20) and because estimates of the TCCON site-to-site bias of 0.4 ppm (one-sigma; Wunch et al., 2016) are significant for carbon cycle studies. As an example of the importance of small biases, Reuter et al. (2014) demonstrated that a gradient of 0.5 ppm in column CO_2 across Europe was associated with a change in flux over that region of about –500 Tg C per year. This increased sink over Europe using a regional model is consistent with the inversion intercomparison of Houweling et al. (2015), who found that assimilating GOSAT column CO_2 retrievals in global inversion models caused an increase of about 700 Tg C per year in the European sink, with a compensating increase

in the northern Africa source of about 900 Tg C per year. These shifts in emissions were associated with degraded agreement with unassimilated *in situ* observations from both surface observation sites and aircraft campaigns. For comparison, the *in situ* assimilation models collected for this chapter estimate a modest sink of 219 ± 405 Tg C per year in Europe and a negligible source of 13 ± 281 Tg C per year in northern Africa over the 2004 to 2013 period. These uncertainties, which comprise both interannual variability and intermodel differences in the inversions, are relatively large but still appear inconsistent with the GOSAT-driven flux increments reported in Houweling et al. (2015). In the relatively short time that GOSAT and OCO-2 have been collecting data, significant progress has been made in identifying and correcting biases in those datasets. Progress also is needed in understanding the time and space scales of remote-sensing data least susceptible to bias and how to assimilate these retrievals jointly with *in situ* data having less bias. Moving forward, more measurements will be key, including expansion of AirCore (Karion et al., 2010) and commercial aircraft observations (Basu et al., 2014) that will enable better assessment and utilization of both ground- and space-based total column CO_2 and CH_4 remote-sensing data.

Next-Generation Measurements

Atmospheric measurements will play an important role in addressing these critical questions on the present and future state of both anthropogenic and biogenic components of the North American carbon cycle. The following is a list of potential, yet achievable, atmospheric measurement approaches that could dramatically change the current view of the North American (and global) carbon cycle.

A. **Commercial Aircraft CO_2 and CH_4 Observations.** The Comprehensive Observation Network for Trace gases by Airliner (CONTRAIL) program has measured GHGs from commercial aircraft for nearly two decades (Matsueda et al., 2008). A similar European effort, In-service Aircraft for a Global Observing System (IAGOS) project (Filges et al., 2015), is not yet fully operational for GHG measurements. The technology exists for unattended, high-accuracy airborne CO_2 and CH_4 measurements (Karion et al., 2013), and deploying instruments aboard 40 domestic U.S. commercial aircraft could result in approximately 500 vertical profiles per day, radically changing CO_2 and CH_4 data density over North America.

B. **Greatly Expanded $\Delta^{14}CO_2$ Measurements.** Recently, Basu et al. (2016) demonstrated that expanding the U.S. network of $\Delta^{14}CO_2$ measurements from about 800 per year to 5,000 per year, as recommended by the U.S. National Research Council (Pacala et al., 2010), could allow for atmospherically based determination of U.S. fossil fuel CO_2 emissions to within 5%, complementing official U.S. EPA inventory-based estimates. In addition to $^{14}CO_2$, other tracers such as CO, non-methane hydrocarbons, halogenated species, and $^{14}CH_4$ (for fossil CH_4 identification) can serve as powerful constraints on emissions, both in total and by sector.

C. **Upcoming Satellite-Based CO_2 and CH_4 Sensors**. These sensors, including GOSAT-2, OCO-3, TanSat (China), Geostationary Carbon Cycle Observatory (GeoCARB; NASA), MERLIN (France and Germany), TROPOMI (European Space Agency), and others (Ciais et al., 2014) likely will enable dramatically increased spatial coverage of total column CO_2, CH_4, and other gases. For the utility of these data to be maximized, existing challenges associated with aerosols, characterization of the ocean and land surface, clouds, daylight, and, more generally, the linkage to formal gas concentration scales must be overcome. GOSAT and OCO-2, and particularly their planned successors, also will yield information on chlorophyll fluorescence (SIF), which has potential as a marker of time and space patterns of plant photosynthesis.

D. **NEON.** If built out as planned, NEON (National Science Foundation) will provide calibrated CO_2 measurements on towers over a variety of North American biomes that will add

significantly to the North American CO_2 observational dataset.

E. **Additional Gas Tracers.** As with anthropogenic ancillary tracers (see B), numerous gases can serve as tracers of terrestrial ecosystem processes. Gross primary production fluxes are closely linked to atmospheric gradients in COS and $\Delta^{17}O$ (anomalies in the ^{18}O:^{17}O ratio of CO_2; e.g., Campbell et al., 2008; Thiemens et al., 2014). Atmospheric $\delta^{13}CO_2$ is sensitive to the impact of regional-scale moisture stress on terrestrial photosynthesis (Ballantyne et al., 2010) and can distinguish C_3 and C_4 plant productivity. Schwietzke et al. (2016) showed the potential for $\delta^{13}CH_4$ observations to distinguish fossil fuel CH_4 emissions from other sources. Measurements of the $\delta^{18}O$ of CO_2 reflect both biospheric processes and changes in the hydrological cycle (Ciais et al., 1997; Flanagan et al., 1997; Miller et al., 1999).

F. **Measurements to Improve Atmospheric Transport Simulation.** Such measurements are critical for fully extracting the information content of atmospheric CO_2 and CH_4 data. Better understanding and parameterizing of atmospheric transport are critical. Near-surface GHG concentrations are a sensitive function of the planetary boundary-layer mixing height, wind speed, and wind direction. Measurements of the vertical wind structure and boundary-layer depth using rawinsonde, LIDAR, and radar, and assimilating these data into atmospheric transport models, can improve atmospheric transport significantly (Deng et al., 2017). Simulated CO_2 transport is sensitive to boundary-layer mixing, convective cloud transport, synoptic weather patterns, and the surface energy balance, all of which can be difficult to simulate with the high accuracy and precision required for atmospheric inversions. Fortunately, decades of weather forecasting research provide a strong foundation for improving the meteorological reanalyses used in atmospheric inversions. Observational programs that merge meteorological measurements with high-density GHG data (e.g., ACT-America) are aimed at advancing this aspect of atmospheric inverse modeling. In addition, measurements of tracers such as water vapor isotopic ratios, sulfur hexafluoride (SF_6), and even $^{14}CO_2$, where emissions are relatively well known (Turnbull et al., 2008), also can constrain simulated transport (Denning et al., 1999; Patra et al., 2011; Peters et al., 2004).

SUPPORTING EVIDENCE

KEY FINDING 1

Global concentrations of carbon dioxide (CO_2) and methane (CH_4) have increased almost linearly since the *First State of the Carbon Cycle Report* (CCSP 2007; see Figure 8.1, p. 339). Over the period 2004 to 2013, global growth rates estimated from the National Oceanic and Atmospheric Administration's (NOAA) marine boundary layer network average 2.0 ± 0.1 parts per million (ppm) per year for CO_2 and 3.8 ± 0.5 parts per billion (ppb) per year for CH_4. Global mean CO_2 abundance as of 2013 was 395 ppm (compared to preindustrial levels of about 280 ppm), and CH_4 stands at more than 1,810 ppb (compared to preindustrial levels of about 720 ppb); (*very high confidence*).

Description of evidence base

Global mean atmospheric growth rates and abundances of CO_2 and CH_4 are derived from publicly available tables on NOAA websites: 1) www.esrl.noaa.gov/gmd/ccgg/trends/global.html and 2) www.esrl.noaa.gov/gmd/ccgg/trends_ch4/.

Major uncertainties

The averages were calculated from the regularly updated marine boundary layer sites of NOAA's Global Greenhouse Gas Reference Network. These averages are not associated with any recent literature. The methodology used to construct the global "surfaces" from which the global averages are computed is described in Masarie and Tans (1995). The uncertainties originate primarily from the incomplete sampling of the marine boundary layer by the NOAA network and the uncertainty associated with smoothing the raw data prior to creating the global surface. Measurement uncertainty of CO_2 and CH_4 is a minor component. Uncertainty calculations are described in detail at: www.esrl.noaa.gov/gmd/ccgg/mbl/mbl.html. While the atmospheric CO_2 growth rate is relatively stable, there is strong decadal and interannual variability of CH_4 emissions, making computation of an average inherently sensitive to the choice of time period. For instance, the CH_4 growth rate averaged over 1997 to 2006 was 2.8 ppb per year, whereas over 2007 to 2015, it was instead 7.0 ppb per year.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

NOAA data are the gold standard for determining global growth rates and abundances because of extensive global coverage and high internal network compatibility, including high measurement precision. The trends and growth rates also agree well with estimates from other laboratories.

Summary sentence or paragraph that integrates the above information

NOAA CO_2 and CH_4 trends and abundances are publicly available, fully traceable, and represent the most comprehensive description of global CO_2 and CH_4.

KEY FINDING 2

Inverse model analyses of atmospheric CO_2 data suggest substantial interannual variability in net carbon uptake over North America. Over the period 2004 to 2013, North American fossil fuel emissions from inventories average 1,774 ± 24 teragrams of carbon (Tg C) per year, partially offset by the land carbon sink of 699 ± 82 Tg C year. Additionally, inversion models suggest a trend

toward an increasing sink during the period 2004 to 2013. These results contrast with the U.S. land sink estimates reported to the United Nations Framework Convention on Climate Change, which are smaller and show very little trend or interannual variability.

Description of evidence base

Fossil fuel emissions are from Carbon Dioxide Information Analysis Center (CDIAC) estimates (available from the U.S. Department of Energy's Environmental Systems Science Data Infrastructure for a Virtual Ecosystem [ESS-DIVE] data archive, ess-dive.lbl.gov). The land carbon sink is based on the 10-year average of North American annual fluxes from four global inverse models, specified in the text. The error reported is twice the standard error of the mean of the 10 years and for the four models and mostly represents the amount of interannual variability. The evidence for a trend is based on a linear least-squares regression. The comparison of variability with the U.S. Environmental Protection Agency's (EPA) estimate of the U.S. land sink is based on EPA data accessed at www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2015.

Major uncertainties

Fossil fuel emissions uncertainty is very low (see Appendix E: Fossil Fuel Emissions Estimates for North America, p. 839). Long-term means of CO_2 sources and sinks derived from a given inverse model are highly uncertain. However, the interannual variability of fluxes from different models tends to agree well, suggesting lower uncertainty. EPA land flux estimates may not exhibit enough variability due to the U.S. Forest Service methodology, upon which EPA's estimates are largely based.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Fossil fuel uncertainty at the national, annual scale has the smallest uncertainty because it can be constrained by highly accurate information on imports and exports and internal usage. Inverse model-based estimates of CO_2 sources and sinks contain numerous random and systematic errors including biases associated with wind fields and parameterization of vertical mixing. Because models exhibit different mean atmospheric transport, their long-term average fluxes can differ significantly. However, the interannual variability of fluxes among inverse models is much more similar, meaning that the difference between the inverse model and EPA flux variability is likely to be robust.

Estimated likelihood of impact or consequence, including short description of basis of estimate

The contrast between variability exhibited in the inverse model and the EPA estimates of land sink variability could cause EPA to reexamine its methodologies. Additionally, the emerging evidence that the North American CO_2 sink is growing also could spur research in the "bottom-up" community and impact policy decisions.

Summary sentence or paragraph that integrates the above information

Regularly produced inverse modeling estimates of CO_2 sources and sinks over North America are beginning to provide valuable information at least on interannual variability of terrestrial ecosystem fluxes.

KEY FINDING 3

During most of the study period covered by the *Second State of the Carbon Cycle Report* (2004 to 2012), inverse model analyses of atmospheric CH_4 data show minimal interannual variability in emissions and no robust evidence of trends in either temperate or boreal regions. The absence of a trend in North American CH_4 emissions contrasts starkly with global emissions, which show significant growth since 2007. Methane emissions for North America over the period 2004 to 2009 estimated from six inverse models average 66 ± 2 Tg CH_4 per year. Over the same period, EPA-reported CH_4 emissions equate to a climate impact of 13% of CO_2 emissions, given a 100-year time horizon.

Description of evidence base

The conclusions of minimal interannual variability (standard deviation), trend (slope and its uncertainty), and mean flux are all based on fluxes from 14 inverse models used in the global CH_4 budget analysis of the Global Carbon Project (Saunois et al., 2016). The 13% ratio of CH_4 to CO_2 warming impact is based on EPA CH_4 and CO_2 emission estimates using a 100-year global warming potential (GWP) value of 28.

Major uncertainties

Total CH_4 emissions for North America include the inversely derived value of 60 Tg CH_4 per year and the EPA anthropogenic emissions estimate for the United States, which would impact the 13% ratio. Inverse models are subject to poorly known uncertainties stemming from the use of biased priors, imperfect models of atmospheric transport, and the sparse network of *in situ* measurements.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Total emissions have a high uncertainty (not reflected in the variability value stated in the Key Finding); note that EPA does not provide an uncertainty for its estimate. The absence of any trend has higher confidence, because numerous models with different methodologies contributed to this finding. However, the models used in the comparison did not uniformly cover the 2000 to 2013 period, making the conclusion less robust than that for CO_2. On the other hand, the smaller variability relative to CO_2 is consistent across models and is more robust. The 13% value is uncertain because of EPA's CH_4 emissions estimate and, to a lesser extent, the GWP uncertainty.

Estimated likelihood of impact or consequence, including short description of basis of estimate

The finding that CH_4 is unlikely to have a temperate North American trend different from zero is significant, because there is great interest in the cumulative radiative forcing impact of CH_4 emissions from the oil and gas sector. Moreover, while not a new finding, the simple calculation of CH_4 having only 13% of the warming impact as CO_2 should remind policymakers and scientists that CO_2 emissions are substantially more important.

Summary sentence or paragraph that integrates the above information

The global and North American emissions were derived using atmospheric CH_4 data assimilated in a wide variety of CH_4 inverse models using both *in situ* and remote-sensing data. Although a consistent picture is emerging, the results are more uncertain than those for CO_2, because estimates are not produced regularly over consistent timescales.

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9 Forests

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KEY FINDINGS

1. Net uptake of 217 teragrams of carbon (Tg C) per year by the forest sector in North America is well documented and has persisted at about this level over the last decade. The strength of net carbon uptake varies regionally, with about 80% of the North American forest carbon sink occurring within the United States (*high confidence, very likely*).

2. Forest regrowth following historical clearing plays a substantial role in determining the size of the forest carbon sink, but studies also suggest sizeable contributions from growth enhancements such as carbon dioxide fertilization, nitrogen deposition, or climate trends supporting accelerated growth (*medium confidence*). Resolving each factor's contribution is a major challenge and critical for developing reliable predictions.

3. Annual harvest removals from forestry operations in select regions decrease forest carbon stocks, but this decline in stocks is balanced by post-harvest recovery and regrowth in forestlands that were harvested in prior years. Removal, processing, and use of harvested biomass causes carbon emissions outside of forests, offsetting a substantial portion (about half) of the net carbon sink in North American forests (*high confidence*).

4. Recent trends in some disturbance rates (e.g., wildfires and insects) have diminished the strength of net forest carbon uptake across much of North America. Net loss of forest carbon stocks from land conversions reduced sink strength across the continent by 11 Tg C per year, with carbon losses from forest conversion exceeding carbon gains from afforestation and reforestation (*medium confidence*).

5. Several factors driving the carbon sink in North American forests are expected to decline over coming decades, and an increasing rate of natural disturbance could further diminish current net carbon uptake (*medium confidence*).

Note: Confidence levels are provided as appropriate for quantitative, but not qualitative, Key Findings and statements.

9.1 Introduction

The forest land area of North America increased from an estimated 719 million hectares (ha) in 2005 to more than 723 million ha in 2015 and now represents 36% of the land area in North America and 18% of the world's forest land area (FAO 2016b). The increase in forest land area over the last decade was driven entirely by gains in the United States, while Canada and Mexico both lost forestland (see Table 9.1, p. 367). The area of other wooded lands also increased in North America over the last decade, with substantial gains in the United States, no change in Canada, and loss in Mexico.

Forest ecosystems are the largest terrestrial carbon sink on Earth, and their management has been recognized as a relatively cost-effective strategy for offsetting greenhouse gas (GHG) emissions (Canadell and Schulze 2014). In North America, forests—including urban forests, woodlands, and the products obtained from them—play a major role in the carbon cycle (Goodale et al., 2002). Since this report includes forestland from Canada, Mexico, and the United States, forestland is defined according to the Global Forest Resource Assessments from the United Nations Food and Agricultural Organization (FAO 2010, 2016b). This definition also is widely used for land representation in GHG reporting to the United Nations Framework Convention on Climate Change (UNFCCC; see U.S. EPA 2018) to ensure consistency and comparability in national reporting. Forest area is defined as land spanning greater than 0.5 ha with trees higher than 5 m and canopy cover of more than 10%, or trees able to reach these thresholds *in situ*. Other wooded lands are

defined as land not classified as forest, spanning greater than 0.5 ha with 1) trees higher than 5 m and a canopy cover of 5% to 10%; 2) trees able to reach these thresholds *in situ*; or 3) land with a combined cover of shrubs, bushes, and trees above 10%. Forests and other wooded land do not include land predominantly used for agriculture or urban purposes (FAO 2010). For this reason, urban forests are not included in this chapter, but their contribution to total carbon stocks and stock changes is described.

Forests' capacity to uptake and store carbon is influenced by many socioeconomic and biophysical factors (Caspersen et al., 2000; Joos et al., 2002; Birdsey et al., 2006; Zhang et al., 2012). Sustained investment in afforestation, reforestation, and improved forest management is an option for elevating the role forests play in future climate mitigation. This chapter presents the most recent estimates of carbon stocks and stock changes across the continuum of land with trees in North America and highlights advances in forest carbon cycle science since the *First State of the Carbon Cycle Report* (SOCCR1; CCSP 2007).

9.2 Historical Context

Forestland, and thus forest carbon, has changed substantially in North America over the last several hundred years. In the United States, for example, forestland amounts to an estimated 72% of the area that was forested in 1630, with roughly 120 million ha converted to other uses (mainly agricultural) primarily from 1850 to 1910 (Smith et al., 2009). National assessments of forest land area and carbon dynamics have been conducted in Canada, Mexico, and the United States, but the motivation for these reports and the methods and data sources they use differ substantially among countries. In recent decades, official government estimates of forest land area, forest carbon stocks, and stock changes have been compiled following guidelines from the Intergovernmental Panel on Climate Change (IPCC 2003, 2006). However, the methods for estimating carbon stocks and their changes (e.g., stock difference versus gain-loss) still differ based on country-specific circumstances, but estimation approaches have evolved as new and better information has become available in each country. Of the numerous key findings SOCCR1 identified on the

Table 9.1. Estimated Area (in Thousands of Hectares) of Forest and Other Wooded Land in North America in 2005 and 2015

Country[a]	Forestland[b]		Other Wooded Land[c]	
	2005	2015	2005	2015
Canada	347,576	347,069	40,866	40,866
Mexico	67,083	66,040	20,378	19,715
United States	304,757	310,095	15,452	21,279
Total[d]	719,416****	723,204****	76,696****	81,860****

Notes

a) Estimates based on FAO (2016b).

b) Defined as land spanning greater than 0.5 hectare (ha) with trees higher than 5 m and a canopy cover of more than 10%, or trees able to reach these thresholds *in situ* (FAO 2010).

c) Defined as land not classified as forest, spanning greater than 0.5 ha with trees higher than 5 m and a canopy cover of 5% to 10%; or trees able to reach these thresholds *in situ*; or with a combined cover of shrubs, bushes, and trees above 10% (FAO 2010).

d) Uncertainty estimates (noted by asterisks) follow the convention described in Treatment of Uncertainty in SOCCR2, p. 16, in the Preface.

role of forests in the North American carbon cycle, many (e.g., land-use change) continue to be relevant 10 years later, along with several emerging topics (e.g., climate feedbacks).

9.3 Current Understanding of Carbon Fluxes and Stocks

9.3.1 Carbon Stocks and Pools

Forests

Carbon is continuously cycled among the atmosphere and ecosystem carbon storage pools (i.e., above- and belowground biomass, dead wood, litter, and soil). This cycling is driven by biogeochemical processes in forests (e.g., photosynthesis, respiration, decomposition, and disturbances such as fires or pest outbreaks) and anthropogenic activities (e.g., harvesting, thinning, and replanting). As trees photosynthesize and allocate a portion of this carbon to growth, carbon is removed from the atmosphere and stored in living tree biomass. As live biomass dies, litter and dead wood are deposited on the forest floor and in the soil below ground (e.g., dead roots). The carbon in these dead components is either stored as soil organic matter or released to the atmosphere or water through decomposition by microorganisms. When forests are harvested, some of the biomass carbon is transferred to harvested wood products from which it may be lost to the atmosphere (burned) in the year of the harvest (e.g., fuelwood [including pellets] and mill residues) or stored for a few years (e.g., paper products) to centuries (e.g., sawnwood or panels used in buildings) (IPCC 2006; Skog 2008).

Carbon stocks in North American forests have continued to increase over the last decade to an estimated 103,110 teragrams of carbon (Tg C), of which 32% is in live biomass and 68% is in dead organic matter (see Table 9.2, this page; Stinson et al., 2011; Köhl et al., 2015; FAO 2010, 2016b; U.S. EPA 2018). The increase in total carbon stocks is largely due to increases in aboveground biomass in the eastern United States, even as carbon stocks in Canada decreased slightly in recent years because of natural disturbances such as insects and wildfire (Stinson et al., 2011; Köhl et al., 2015; FAO 2010, 2016b; U.S. EPA 2018; ECCC 2016).

Carbon density (i.e., the amount of carbon stored per unit of land area) is highly variable (e.g., see Figure 9.1, p. 369, for the distribution of aboveground live biomass density on forestland in North America). The estimated carbon density in North American forests is 142.4 megagrams of carbon (Mg C) per hectare. In Canada, the largest carbon densities are in boreal and cordilleran forests (ECCC 2016; Kurz et al., 2013). In the United States, forests of the Northeast, upper Midwest, Pacific Coast, and Alaska continue to store the most

Table 9.2. Forest Carbon Stocks (in Teragrams of Carbon) by Carbon Pool in North America

Country	Aboveground Biomass	Belowground Biomass	Dead Wood	Litter	Soil
Canada[a]	11,162	2,746	4,683	11,666	19,729
Mexico[b]	1,597	396	2	NA[c]	NA
United States[d]	14,182	2,923	2,570	2,680	28,774
Total[e]	26,941****	6,065****	7,255****	14,346****	48,503****

Notes

a) Estimates based on FAO (2010).

b) Estimates based on FAO (2016b).

c) Not applicable.

d) Estimates based on U.S. EPA (2018).

e) Uncertainty estimates (noted by asterisks) follow the convention described in Treatment of Uncertainty in SOCCR2, p. 16, in the Preface.

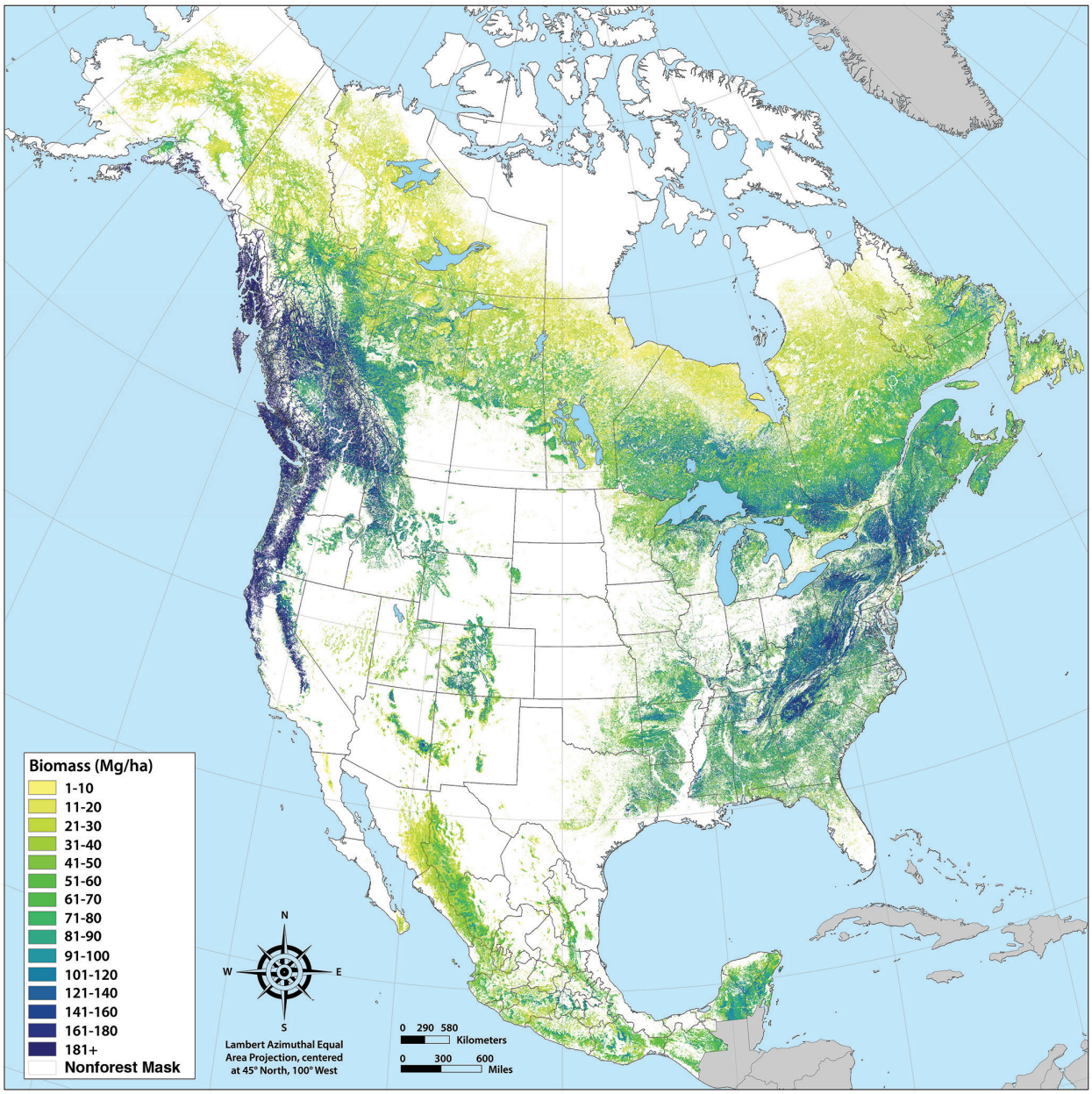


Figure 9.1. Hectares (ha) of Aboveground Forest Biomass Across North America. This comprehensive map combines four independently developed maps of biomass for Canada, Alaska, the conterminous United States, and Mexico (Beaudoin et al., 2014; Blackard et al., 2008; Wilson et al., 2013; MREDD+ Alliance 2013). A common legend, map projection, and spatial resolution of 250 m were applied to the individual maps with no attempt to harmonize the methods used for each of the original map products. Biomass of nonforest areas is masked by including only land-cover and land-use categories 1–6 from the North American Land Change Monitoring System (NALCMS 2018). Base years of the original maps are Canada, 2001; Alaska, 2004; conterminous United States, 2000–2009; and Mexico, 2007. [Figure source: Kevin McCullough, U.S. Forest Service. North American Biomass and Disturbance Mapping Working Group, 2014.]

carbon (U.S. EPA 2018; see Figure ES.1, p. 23, for a description of the areal extent of regions in the United States). In Mexico, forest carbon stocks are split fairly evenly among temperate, tropical, and semiarid forests (INECC/SEMARNAT 2015).

Woodlands

Woodlands are areas with tree coverage that falls between savanna and forest biomes. In the United States, for example, tree cover for woodlands does not meet the criteria for forestlands or agroforestry. Most woodlands occur in a matrix of grass vegetation and have been expanding in recent decades as trees and woody shrubs encroach on grasslands around the world, including in the western United States (Archer 1994; Briggs et al., 2002; Weisberg et al., 2007). For example, Asner et al. (2003) estimated a 10% increase in woody plant cover over a 40,000 ha area of northern Texas from 1937 to 1999 and an associated biomass carbon stock increase of 120 grams of carbon (g C) per m^2. In the Intermountain West, woodland areas increased by about 1.3 million ha from 2005 to 2010 and resulted in an estimated net carbon stock increase of 6,439 Mg in biomass, litter, and dead wood (Coulston et al., 2016; Ogle and Zeigler 2016). Woody encroachment also could affect soil carbon stocks (Hibbard et al., 2001), although this may not be the case in all woodland systems (Hughes et al., 2006) and may vary depending on the climate (Jackson et al., 2002).

9.3.2 Fluxes

North American forests currently act as a net sink for atmospheric carbon dioxide (CO_2; Hayes et al., 2012; King et al., 2015). A summary of data reported in recent GHG inventories (ECCC 2016; INECC/SEMARNAT 2015; U.S. EPA 2018) suggests that the North American carbon sink in forestland remaining forestland was about 325 Tg C per year over the last decade, with U.S. forests accounting for most of the sink (see Table 9.3, p. 371, and Box 9.1, Clarifying Forest Carbon Flows and Their Relation to Emissions or Removals of Atmospheric Carbon, p. 372, for an explanation of associated terms). This sink results from photosynthetic uptake that exceeds the releases of forest carbon by plant and heterotrophic respiration and from fire. A sizeable portion of the net uptake of atmospheric carbon within forestlands is offset by harvest-related emissions. These emissions include wood processing—from log removal to product generation—as well as the decay and combustion of harvested wood products, which together release about 124 Tg C per year. Thus, the net forest sector–atmosphere flux for North America is estimated to be a sink of 217 Tg C per year over roughly the last decade. Urban trees are estimated to uptake another 27 Tg C per year in the United States and Canada. Note that the fluxes reported here represent contemporary rates in recent years, spatially integrated to the country scale. Future legacies resulting from contemporary or historical drivers of forest carbon dynamics are not included. Such trends are particularly important if those drivers exhibit long-term trends, as in a decline or increase in harvest or natural disturbance rates, which would lead to trends in carbon fluxes.

Net forest carbon gain and loss constitute a source of 11 Tg C per year in North America. In the United States, net emissions from forest carbon losses encompass losses of aboveground biomass from conversion to croplands, grasslands, and settlements and include both prompt and residual legacy emissions from conversions that occurred over a 20-year time frame. Canada adopted a similar approach for quantifying emissions but accounted for conversions to croplands, settlements, and wetlands. The U.S. and Canadian estimated flux from forest carbon gains and losses includes all live biomass, dead organic matter, and soil carbon components.

Forests are generally believed to neither release nor absorb substantial quantities of methane (CH_4), though upland soils can act as modest sinks and forested wetlands can be CH_4 sources. However, forest fires release CH_4, contributing a 25-year global warming potential (GWP) of 9 Tg of CO_2 equivalent[1] (CO_2e) per year in Canada and releasing 0.22 Tg CH_4

[1] Carbon dioxide equivalent (CO_2e): Amount of CO_2 that would produce the same effect on the radiative balance of Earth's climate system as another greenhouse gas, such as methane (CH_4) or nitrous oxide (N_2O), on a 25-year timescale. For comparison to units of carbon, each kg CO_2e is equivalent to 0.273 kg C (0.273 = 1/3.67). See Box P.2, p. 12, in the Preface for details.

Table 9.3. Net Emissions of Carbon Dioxide Equivalent (CO_2e)[a] for Forestlands from Net Forest Gain and Loss, Tree Growth in Urbanized Settlements, and Harvested Wood Products of Domestic Origin, by Country and Expressed in Teragrams of Carbon (Tg C) per Year

Tg C per Year	Canada[b]	United States[c]	Mexico[d]	Total[k]
1. Net Ecosystem Exchange for Forestland Remaining Forestland[e]	–18	–267	–41	–325****
Stock Change for Forestland Remaining Forestland[e] (Δ Forest C)	–27	154	ND[j]	127
2. Net Flux Due to Forest Area Gain and Loss ($A_{Loss} + A_{Gain}$)	3	0	9	11***
Emissions from Forest Area Loss[f] (A_{Loss})	3	23	12	38
Emissions from Forest Area Gain[g] (A_{Gain})	0	–23	–3	–27
3. Settlements Remaining Settlements[h] (Urban; Net Ecosystem $Production_{settled}$)	–3	–24	ND	–27***
4. Emissions from Biomass Removal and Use[i] (F_{HWP})	35	89	ND	124***
Harvest Removals of Forest Carbon (Harv)	43	113	ND	155
Stock Change for Wood Products (from Harvest Removals – 4)	8	23	ND	31
5. Forest Sector–Atmosphere Exchange (from 1 + 2 + 3 + 4; Δ Atmos. C)	16	–201	–32	–217****

Emissions are from 2000 to 2014 for the United States, from 2006 to 2015 for Canada, and the 2000s for Mexico. Exchanges with the atmosphere (e.g., terms 1, 2, 3, 4, 5) are assigned a negative sign for transfers out of the atmosphere (also known as removals or sinks), but the negative sign is dropped in the text when the direction of transfer is specified with terminology. Stock changes in forestlands and in wood products are assigned a positive sign if they are increasing (see Box 9.1, Clarifying Forest Carbon Flows and Their Relation to Emissions or Removals of Atmospheric Carbon, p. 372, for a review of associated terms).

Notes

a) Carbon dioxide equivalent (CO_2e): Amount of CO_2 that would produce the same effect on the radiative balance of Earth's climate system as another greenhouse gas, such as methane (CH_4) or nitrous oxide (N_2O), on a 25-year timescale. For comparison to units of carbon, each kg CO_2e is equivalent to 0.273 kg C (0.273 = 1/3.67). See Box P.2, p. 12, in the Preface for more details.

b) ECCC (2017). Only includes Canada's managed forests for the 10-year period 2006 to 2015.

c) U.S. EPA (2018). Does not include U.S. territories, Hawai'i, or a large portion of interior Alaska (19.7 million hectares), which are not yet fully integrated into the U.S. national inventory program.

d) INECC/SEMARNAT (2015). Includes effects of forest loss and cyclical uses, which account for some of the emissions that would otherwise appear as releases from harvested wood products.

e) Includes net exchange between the atmosphere and forestland remaining forestland, including disturbance emissions that occur within forests such as those from fire combustion and onsite decay of harvest residues. For the United States, this estimate has been calculated from stock change (see c), plus average harvest removals of about 113 Tg C per year (U.S. EPA 2018).

f) Includes emissions from forest conversion to croplands, wetlands, grasslands, and settlements when reported, and including residual emissions for decades after conversion; overlaps with reporting in other land use, land-use change, and forestry (LULUCF) categories.

g) Includes emissions (and removals) from all lands converted to forestland through direct human activity; overlaps with reporting in other LULUCF categories.

h) Also referred to as net growth of urban trees; overlaps with reporting in other LULUCF categories.

i) Includes emissions from harvesting removals of biomass of domestic origin and its use in a range of forest products.

j) No data.

k) Uncertainty estimates (noted by asterisks) follow the convention described in Treatment of Uncertainty in SOCCR2, p. 16, in the Preface.

Box 9.1: Clarifying Forest Carbon Flows and Their Relation to Emissions or Removals of Atmospheric Carbon

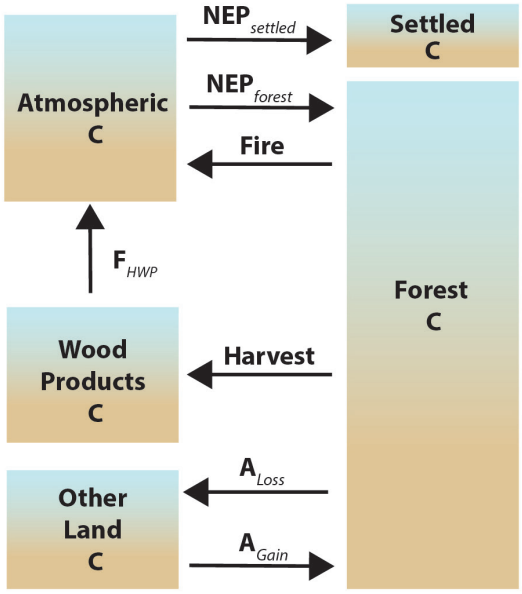
Forests tend to accumulate carbon over time, absorbing carbon dioxide (CO_2) from the atmosphere and storing it as carbon in living biomass, dead organic matter, and mineral soil. The net effect of forests on the atmosphere's store of carbon is reflected in the term "forest net ecosystem production" (NEP_{forest}) or net ecosystem exchange (NEE), which principally represents a forest's metabolic balance between its rate of carbon uptake through photosynthesis and its rate of carbon release as CO_2 through respiration. NEP tends to be positive in forests free of recent disturbance, though climate extremes such as droughts can cause intermittent net carbon releases (NEP < 0).

Disturbance events typically diminish photosynthetic carbon uptake, promptly reducing NEP. Disturbances, including fire and harvesting, also destroy biomass and impose residual respiration releases of carbon from dead biomass as it decays within forests, further decreasing NEP. Fire disturbances (i.e., wildfires and prescribed burns) involve combustion emissions that directly release carbon to the atmosphere, mostly as CO_2 but also as methane, carbon monoxide, volatile organic compounds, and black carbon (see "fire" in Figure 9.2, p. 373).

Harvesting introduces an additional release of forest carbon to the atmosphere through the immediate processing of harvest removals to generate wood products and energy as well as through the combustion and decay of wood products in use. The term F_{HWP} represents the sum of these harvest-related release processes. Some of the harvested biomass (see "harvest" in Figure 9.2, p. 373) is transferred to wood products, a portion of which can reside for decades to centuries either in use (e.g., houses and buildings) or in waste deposits (e.g., landfills). The transfer of forest carbon to long-lived wood products is not itself a direct sink of atmospheric carbon; the sink occurs upstream as part of NEP. Similarly, an increase of carbon stored in wood products should not be interpreted as a sink of atmospheric carbon, but rather the result of a transfer of forest carbon to wood products that exceeds the rate of release of carbon from combustion and decay of legacy wood products. However, if the carbon stocks within a harvested forest recover to their preharvest level faster than releases of the harvested carbon through F_{HWP} plus respiration, a "transient" sink of atmospheric carbon can be created as part of NEP. This sink is transient because it lasts only as long as the excess carbon is stored in wood products, where excess carbon refers to the amount of the originally harvested carbon that has since been recovered by forest regrowth minus the cumulative release of harvested carbon. Correspondingly, shifting harvest removals toward longer-lived wood products can slow F_{HWP}, resulting in an avoided (or delayed) emission of carbon from wood products.

Forest carbon stocks respond not only to the previously mentioned carbon fluxes (e.g., NEPforest, fire, and harvest), but also to gross losses and gains of carbon due to land conversions (AGain and ALoss). Although the reclassification of lands from nonforest to forest (or vice versa) does not itself involve emissions or removals of atmospheric carbon, the processes underlying such reclassifications invariably do. Most important is the residual emission of forest carbon that typically occurs when lands are converted from forest to nonforest. National inventory reports typically include such emissions for 20 years after forest loss, consistent with the estimates in Table 9.3, p. 371, but with methodological differences between countries. Land conversions also complicate agreement between NEE and stock change estimates. For example, NEE for Canada in this chapter was calculated

as the average of the annual fluxes on lands classified as forestland remaining forestland (FLFL) in each reporting year, while the stock change was calculated as the carbon stocks on all FLFL lands in 2015 minus the carbon stocks on all FLFL lands in 2006. Because FLFL area decreased over this interval, carbon stocks in FLFL decreased accordingly, with some of the carbon loss appearing as harvest removals, some involving transfer to other land categories, and neither involving immediate emission to the atmosphere (and thus not included in forestland NEE). For the United States, the estimated stock change presented in this chapter only considers lands that persisted as FLFL for the duration of the reporting interval. This estimate was then used to infer an associated NEE in FLFL after accounting for losses from harvest and fire, but at the risk of omitting NEE associated with lands that entered or left the FLFL category during the reporting interval. Methods of assessing carbon transfers, emissions, and removals associated with lands entering or leaving the forestland class are improving and will continue to subtly adjust the larger picture.



Stock Change in Forestlands:

$\Delta \text{Forest C} = NEP_{forest} - Harvest - Fire + A_{Gain} - A_{Loss}$

Net Atmosphere – Forest Sector Exchange:

$\Delta \text{Atmospheric C} = Fire + F_{HWP} - NEP_{forest} - NEP_{settled}$

Figure 9.2. Flow Diagram of Active Carbon Exchanges and Stores Between the Atmosphere and the Forest Sector.

The store of carbon in the atmosphere responds to NEP-forest and wooded portions of settled lands ($NEP_{settled}$; see Ch. 4: Understanding Urban Carbon Fluxes, p. 189), plus direct fire emissions from forests and emissions from the decay and combustion of harvest removals (FHWP). The atmosphere does not directly experience the effects of reclassified lands, nor the flow of carbon from forests to the wood products sector, though both have implications for atmospheric carbon as previously noted.

per year (ECCC 2016). In the United States, CH_4 emissions from forest fires equate to a 100-year GWP of 8.3 Tg CO_2e per year, or a 25-year GWP of about 33 Tg CO_2e per year (U.S. EPA 2018).

The Canadian forest sector constituted a near-zero carbon exchange with the atmosphere from 2006 to 2015 as net carbon uptake in intact forests was largely balanced by releases from harvested wood products (ECCC 2017; see Table 9.3, p. 371). Intact Canadian forests took up about 18 Tg C per year over this period, but with large interannual variability ranging from a sink of 248 Tg C to a source of 3.5 Tg C per year. This variability was

driven principally by variability in wildfire emissions, ranging from 3 to 75 Tg C per year from 1990 to 2014 (ECCC 2016). Emissions from harvested wood products were about 43 Tg C per year. These estimates pertain solely to Canada's managed forests, which represent about 66% of the country's total forested area (Stinson et al., 2011). In addition, Canada's urban forests contributed a small sink of 3 Tg C per year while land conversions released 3 Tg C per year, with emissions from forest losses exceeding removals from forest gains (ECCC 2016).

U.S. forests took up atmospheric carbon at a rate of about 267 Tg C per year from 2000 to 2015, contributing to a stock change of 154 Tg C per year (U.S. EPA 2018) after harvest removals of about 113 Tg C per year (U.S. EPA 2018; see Table 9.3, p. 371). This estimate accounts for about 77% of the atmospheric carbon sink in North American forests and includes all managed forestlands in the United States, except for those in interior Alaska (19.7 million ha; U.S. EPA 2018), Hawai'i, and the U.S. territories, all of which are not yet fully integrated into the U.S. national inventory program (U.S. Forest Service 2018). Most of the net sink for atmospheric carbon in U.S. forests is in aboveground carbon pools (U.S. EPA 2018). Urban trees are estimated to uptake another 24 Tg C per year. Net uptake in U.S. forestlands (a sink of 267 Tg C per year) substantially exceeds emissions from harvested wood products estimated at 113 Tg C and the net effect of land conversions, estimated at 0 Tg C per year (U.S. EPA 2018). Interannual variability in U.S. fluxes is reportedly small but may be underestimated by current methods.

Mexico's forests are estimated to uptake about 41 Tg C per year, overwhelming the net effects of land conversion estimated to release 9 Tg C per year (INECC/SEMARNAT 2015). Carbon releases from land clearing still exceed carbon uptake from reforestation, but their net effect is more than offset by carbon uptake in intact and degraded forestlands. This assessment departs from SOCCR1, which reported a sizeable net carbon release from Mexico's forests based on a gain-loss analysis that emphasized land change but omitted consideration of carbon accumulation rates in both intact forests and degraded forests, with a corresponding net uptake of atmospheric carbon. Although a complete methodological description is unavailable, the new data sources and methods used in Mexico's national reporting are believed to provide an improved account of the net carbon uptake in forestlands, which was previously underestimated. Estimates are not available for Mexico's carbon release from harvested wood products and carbon uptake by urban trees.

Net carbon uptake in North American forests as documented in national reports is in broad agreement with results from a wide range of sources (Hayes et al., 2012; King et al., 2015), including 1) atmospheric inversion models (Peylin et al., 2013), 2) syntheses of forest inventory and land-change data (Pan et al., 2011), 3) measurements of forest-atmosphere carbon exchange with eddy covariance (Amiro et al., 2010), and 4) ecosystem process models (Sitch et al., 2015). Regions differ widely in their source and sink patterns and drivers. For example, in the United States, the Northeast has a prevailing legacy of carbon uptake from historical land clearing; in the Southeast, carbon uptake is dominated by regrowth from contemporary harvesting; and carbon releases in the West are increasing because of the recent rise in disturbances and environmental stresses (e.g., droughts, insects, and pathogens; Williams et al., 2016). Fluxes also exhibit large spatial variability at landscape scales (Turner et al., 2016; Williams et al., 2016), with neighboring stands ranging from sources to sinks due to a host of factors including time since disturbance, disturbance type and severity, forest type, local climate, site fertility, topographic position, and other edaphic factors.

9.3.3 Harvested Wood Products

Carbon storage and emissions from harvested wood products (including products in use and in landfills) substantially contribute to overall carbon stocks and fluxes from the forest sector (UNFCCC 2003). Although the contribution of harvested wood products is uncertain, some studies suggest that the

worldwide net increase in harvested wood products amounts to about 8% (189 Tg C per year) of the established global forest sink (Pan et al., 2011; Skog et al., 2004). However, wood product accumulation is the result of harvested wood inputs from forests that exceed releases from the decay and combustion of wood products in use. As such, the wood products pool cannot act as a direct sink for atmospheric carbon, but the store's losses do act as a direct source of atmospheric carbon (see Box 9.1, Clarifying Forest Carbon Flows and Their Relation to Emissions or Removals of Atmospheric Carbon, p. 372). Nonetheless, in the United States, Skog (2008) indicates that the amount of carbon in harvested wood products grew at a rate of 25 to 36 Tg C per year from 1990 to 2005. Canada reports an increase in wood products of about 12 to 17 Tg C per year over the same time period, slowing to about 8 Tg C per year from 2006 to 2015 (ECCC 2017). These net increases result from inputs exceeding losses. For example, in the United States, 76% of the annual domestic harvest input to the wood products pool in 2015 (110 Tg C per year) was offset by releases (84 Tg C per year), yielding a corresponding increase in wood products of 26 Tg C (U.S. EPA 2018, Annex 3b, Table A-240). Importantly, the net increase in the harvested wood products pool is contingent upon a sustained or growing rate of harvest removals of forest carbon, or a shift toward products that have a longer residence time. If harvest rates decline (as they did during the economic recession of 2008), net additions to harvested wood products may be lower than emissions from wood harvested in prior years, as was the case in the eastern United States (U.S. EPA 2018).

In 2009, the annual increase in harvested wood products slowed to 15 Tg C and 0 Tg C per year for the United States and Canada, respectively, driven by slowing economic markets, particularly housing. As economies recover, additions to the harvested wood products pool are now returning to prerecession levels, indicating the pool's strong sensitivity to markets. Looking ahead, carbon storage in harvested wood products is expected to increase by about 7 to 8 Tg C per year over the next 25 years (U.S. Department of State 2016).

9.4 Attribution and Trends

9.4.1 Overview

Many of the factors identified in SOCCR1 (CCSP 2007) continue to be important drivers of change in carbon stocks of forest ecosystems and wood products (CCSP 2007). North American forests are highly diverse, and many are changing rapidly. Management (e.g., timber harvesting and cyclical forest uses) is a major driver of carbon dynamics. Land conversions may cause net carbon emissions in North America, even in the United States where gross gains in forestland exceed gross losses. The changing climate and atmospheric chemistry (e.g., nitrogen deposition, tropospheric ozone, and rising atmospheric CO_2 concentrations) are modifying forest growth rates, growth potential, and mortality. Natural disturbances (e.g., wind, fire, and insects and disease) are generally accelerating mortality and modifying forest composition. All these drivers, and their ongoing trends, have important implications for forest carbon policy and management.

9.4.2 Land Use and Land-Use Change

Land use and land-use change can have major implications for land carbon stocks and fluxes and thus are key requirements for UNFCCC reporting. Land-use change, including conversion of nonforestland to forestland, in European nations (Nabuurs et al., 2013) and the United States (Woodall et al., 2015), has taken up a sizeable amount of atmospheric CO_2 since 1990, but this effect is expected to slow in the near future (Coulston et al., 2015; Nabuurs et al., 2013).

The current rate of land-use change in Canada is small, with about 0.02% of Canada's forest area lost each year through deforestation (Dyk et al., 2015; ECCC 2016) or about 30,000 ha of forest lost per year from 2006 to 2015 (ECCC 2017). The gain in forest area through afforestation, vegetation thickening, and expansion of tree lines northward and to higher elevations is not known, so the net balance of forest area change cannot be determined.

In Mexico, land converted to forest contributes a sink of atmospheric carbon of 3.4 Tg C per year.

This sink is more than offset by carbon losses from forest conversion, leading to net carbon emissions of about 8.8 Tg C per year from the balance of forest gains and losses in Mexico (see Table 9.3, p. 371; INECC/SEMARNAT 2015).

Deforestation in the United States occurs at a rate of about 0.12% per year, or 355,000 ha per year (Masek et al., 2011), but is more than offset by forest gain from afforestation. The net effect is a gain in U.S. forest land area of about 0.15% per year, or 430,000 ha per year (Smith et al., 2009; U.S. EPA 2018) between 2006 and 2015, largely converted from grasslands and croplands (U.S. EPA 2018). This nationwide assessment of net changes in forest area masks important region-specific patterns, with the North and Rocky Mountains seeing net gains in forest land area over the past couple decades and the Pacific Coast and South seeing net losses (Smith et al., 2009). The estimated net carbon flux in the United States associated with forestland conversion is approximately zero, with gains in forestland constituting a sink of atmospheric carbon of 23 Tg C per year and losses resulting in emissions of 23 Tg C per year (see Table 9.3, p. 371; U.S. EPA 2018).

9.4.3 Forest Management

Nearly two-thirds of Canada's forests and nearly all forests in the conterminous United States are considered managed lands. Human activities directly influence these lands, and management is mainly for wood products, water, and recreation services, with carbon uptake a secondary outcome. In many of these regions, forest carbon stocks are recovering from historical clearing and thinning dating back to as early as the 1600s. This recovery stimulates forest carbon uptake from both afforestation and carbon accumulation in still-maturing stands. Forest management also has 1) altered forest species composition (e.g., with the establishment of plantations); 2) generally accelerated carbon accumulation rates (Erb et al., 2013); and 3) modified forest soil fertility, both through nutrient gains from fertilizer application and nutrient losses from erosion caused by some harvesting practices. The net effect of such activities on forest carbon stocks and fluxes is unclear. Fire suppression activities have tended to increase forest carbon stocks, and, along with grazing practices, may contribute to woody encroachment. Fuel reduction treatments (e.g., prescribed fire and thinning) often are intended to lower the risk of severe wildfire by reducing crown density, thinning the understory, and reducing fuel loads, all of which may contribute to short-term carbon losses. However, these treatments often lead to carbon storage in wood products, protection of residual trees, and increased growth through reduction of resource competition. Collectively, therefore, fuel reduction treatments may contribute to greater long-term carbon storage than untreated stands (Hurteau et al., 2008; Loudermilk et al., 2016).

9.4.4 Climate and Atmospheric Chemistry

Climate change and extreme weather events, as well as changes in atmospheric chemistry (e.g., nitrogen deposition, tropospheric ozone, and rising atmospheric CO_2 concentrations), affect carbon cycling in forests (Ollinger et al., 2002; Sun et al., 2015; Templer et al., 2012). In general, rising temperatures (Melillo et al., 2011) and atmospheric CO_2 concentrations (Norby et al., 2005) stimulate forest productivity, but the magnitude of these effects depends on soil fertility, particularly nitrogen and phosphorous availability, and the composition of the soil microbial community (Drake et al., 2011; Finzi and Schlesinger 2002; Terrer et al., 2016). Atmospheric nitrogen deposition can increase soil fertility (Thomas et al., 2010), counteract soil resource limitations (e.g., Johnson et al., 1998; Oren et al., 2001), and directly enhance tree growth (Thomas et al., 2010). Climate-induced changes in precipitation may alter soil carbon dynamics and vegetation carbon uptake during periods of inundation, lead to flooding-related tree mortality, and cause soil erosion with losses of particulate and dissolved organic carbon from forests (Frank et al., 2015).

Although some climatic and atmospheric changes can stimulate productivity, they also can negatively affect forest carbon sinks. High temperatures can induce heat-related stress in plants (Peng et al., 2011), worsen drought conditions (Diffenbaugh

et al., 2015), and lead to higher mortality and lower productivity in ecosystems (Anderegg et al., 2015a; Birdsey and Pan 2011). Climate warming also increases night-time ecosystem respiration and reduces net ecosystem production (NEP; Anderegg et al., 2015b). Similarly, the positive effect of rising atmospheric CO_2 and nitrogen availability on net primary production (NPP) can be moderated by elevated tropospheric ozone, which damages plants, reducing their health and productivity (Karnosky et al., 2003; Loya et al., 2003; Pan et al., 2009). Rates of sulfur deposition have declined in recent years, but acid deposition from excess nitrogen remains elevated and contributes to lower soil pH; depletion of labile cations, such as calcium, needed for plant growth (Likens et al., 1996, 2001); and mobilization of aluminum, which is toxic to plants (Aber et al., 1998). The effects of acid deposition on forest carbon storage are mediated through stand age, soil type (e.g., cation-poor sandstones versus calcium-rich limestone), and ultimately the fate of deposited nitrogen. Excess nitrogen deposition can result in nitrogen saturation of biotic and abiotic sinks, altering ecosystem carbon allocation, and lead to a cascade of negative effects on water and air quality that decrease forest productivity. The United States is a global hotspot of nitrogen emissions and deposition, with a steady rate of wet deposition of dissolved inorganic nitrogen from 1985 to 2012. However, the contribution from ammonium has increased relative to nitrate, and deposition is higher in the Midwest and Northeast than in the South and West (Du et al., 2014).

Stimulatory effects of rising CO_2 on aboveground forest productivity have not been matched by a concomitant increase in soil carbon, the largest carbon pool in forests and one that does not turn over very quickly (Lichter et al., 2008; van Groenigen et al., 2014). Thus, larger litter inputs to soils without an increase in soil carbon stocks implies an accelerated rate of carbon cycling in global forest ecosystems (Pan et al., 2013). Moreover, GHGs are returned to the atmosphere through emissions of CO_2 from harvested products; emissions of CO_2, CH_4, and nitrous oxide (N_2O) from biomass burning; and evasion of CO_2 from streams and rivers (Kim and Tanaka 2003; Turner et al., 2013). These emissions are expected to offset a portion of the gains in productivity from afforestation following disturbance and climatic and atmospheric changes (Turner et al., 2013). Furthermore, severe warming of forest soils has been shown to accelerate soil organic matter decay and result in net loss of soil carbon emitted as CO_2 (Melillo et al., 2017). Given the wide range of forest responses, better understanding of the effects of climatic and atmospheric changes continues to be a high research priority in the United States.

9.4.5 Natural Disturbances

Natural disturbances are widespread across North America (see Figure 9.3, p. 378) and play an important role in the forest carbon cycle (Hicke et al., 2012; Odum 1969; Williams et al., 2016), affecting NPP and heterotrophic respiration, transferring carbon from live to dead pools, and involving direct emissions (e.g., from fires [French et al., 2011; Ghimire et al., 2012]). These disturbances include wildfires, insects and pathogens, droughts, floods, and severe wind events (Frank et al., 2015; Tian et al., 2015). Severe disturbances typically cause an immediate reduction in stand-level productivity, transfer carbon from live to dead stores, and increase decomposition. These effects generally are followed by a gradual increase in productivity and decrease in decomposition as the stand recovers. Initial net carbon release immediately after severe disturbances gives way to net carbon uptake as a forest regrows, but the full effect on atmospheric CO_2 depends also on the timing of disturbance-induced CO_2 releases. Carbon impacts of disturbance vary with several key features including disturbance type and severity, temporal sequence of events, and biotic and climatic conditions of regeneration (Hicke et al., 2012; Williams et al., 2016).

The extent, severity, and frequency of natural disturbances have increased in recent decades (Allen et al., 2010; Hicke et al., 2013; see Figure 9.4, p. 379), likely influenced by recent climate change and human activities. Western regions of Canada and the United States have experienced substantial die-offs recently from wildfire, insect outbreak,

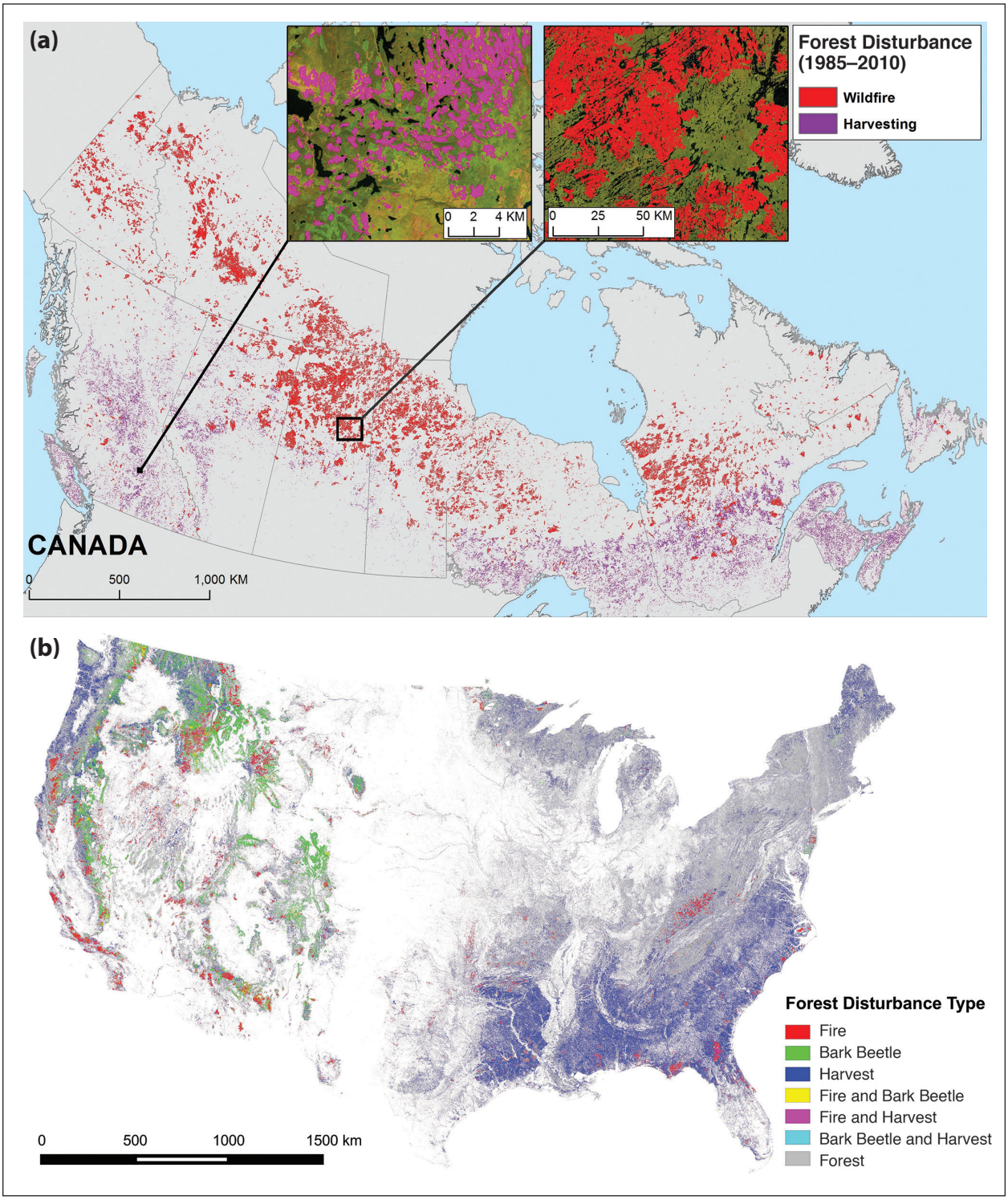


Figure 9.3. Satellite-Derived Distribution of Major Forest Disturbances by Type for Canada (a) and the United States (b). Canadian disturbance data, spanning 1985 to 2010, are based on Hermosilla et al. (2016) and White et al. (2017). U.S. disturbance data (based on Williams et al., 2016) include harvests from 1986 to 2010, fires from 1984 to 2014, and bark beetles from 1997 to 2014. [Figure sources: **(a)** Mike Wulder and Joanne White, Canadian Forest Service, Natural Resources Canada. **(b)** Reprinted from Williams et al., 2016, copyright Elsevier, used with permission.]

and drought disturbances. These events have led to widespread tree mortality, with fire and insects alone affecting up to 9% of the live tree carbon stocks in western U.S. forests (Ghimire et al., 2012, 2015; Hicke et al., 2013) and with insects also having a substantial and prolonged effect in British Columbia (Kurz et al., 2008a, 2008b). Disturbance impacts on region-wide carbon dynamics can be large and result in sizeable interannual variability in the forest carbon balance (see Figure 9.5, p. 380), and landscapes often contain offsetting effects of large carbon releases in small areas that recently experienced severe disturbance and modest carbon uptake in larger areas at various stages of recovery from prior disturbance. In eastern North America, native and invasive forest insects play important roles locally (Clark et al., 2010) and regionally (Kurz and Apps 1999). Insect damage in the United States is estimated to result in the loss of about 20 Tg of live carbon stocks per year, though release to the atmosphere through decomposition can be delayed for decades. Similar, if not larger, losses have been reported for Canada (Kurz et al., 2008a, 2008b). U.S. wildfires lead to emissions of about 40 Tg C per year, with large year to year variability. Windstorms cause an average annual loss of about 35 Tg of live carbon stocks in the United States alone (Williams et al., 2016), largely from hurricanes in the Southeast that have major individual impacts (Chambers et al., 2007; Fisk et al., 2013). Windstorm losses of live biomass are released to the atmosphere only gradually and typically are offset by forest regrowth, leading to a steady long-term effect on atmospheric carbon (Fisk et al., 2013; Zeng et al., 2009). Droughts in the United States and Canada have resulted in punctuated and widespread reductions in forest productivity (Schwalm et al., 2010) as well as tree mortality (Anderegg et al., 2013a, 2013b; Hogg et al., 2008; Michaelian et al., 2011; Peng et al., 2011; Potter 2016; van Mantgem et al., 2009) that together can cause sizeable declines in NEP and the strength of the forest carbon sink (Brzostek et al., 2014; Ma et al., 2012; Schwalm et al., 2012).

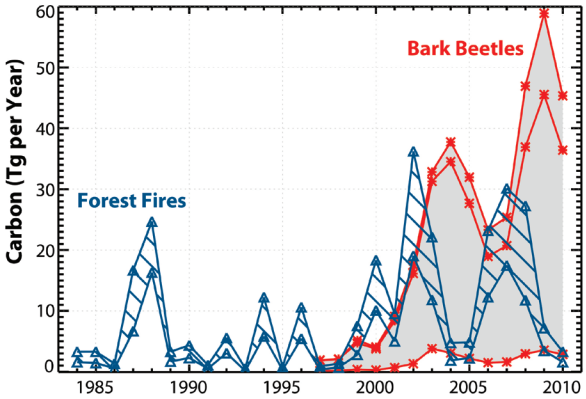


Figure 9.4. Teragrams (Tg) of Carbon in Western U.S. Trees Killed by Disturbances. The impacts of major bark beetle disturbances (1997 to 2010; red lines represent upper, middle, and lower estimates; gray shading indicates range between upper and lower estimates) and forest fires (1984 to 2010; blue lines represent moderate and moderate plus high-severity burned areas; hatching indicates range between moderate and moderate plus high-severity burned areas) are shown. [Figure source: Redrawn from Hicke et al., 2013, used with permission under a Creative Commons license (CC_By_3.0).]

9.4.6 Projections

Accounting for land-use change, management, disturbance, and forest aging, some models project that U.S. forests will continue taking up carbon but at declining rates, largely because of land-use dynamics and aging forests (USDA-OCE 2016; Wear and Coulston 2015). After 20 years of net gains, forest area is projected to level and then decline gradually after 2030 due to ongoing population growth and declining afforestation on agricultural lands (U.S. Forest Service 2012; Wear and Coulston 2015), though projections differ depending on assumptions about how macroeconomic and market trends will drive land use. In the western United States, aging forests coupled with disturbance dynamics are projected to diminish carbon uptake to negligible levels by midcentury. In the East, younger productive forests are expected to have high carbon uptake rates, though harvest-related emissions substantially reduce the net effect on atmospheric carbon.

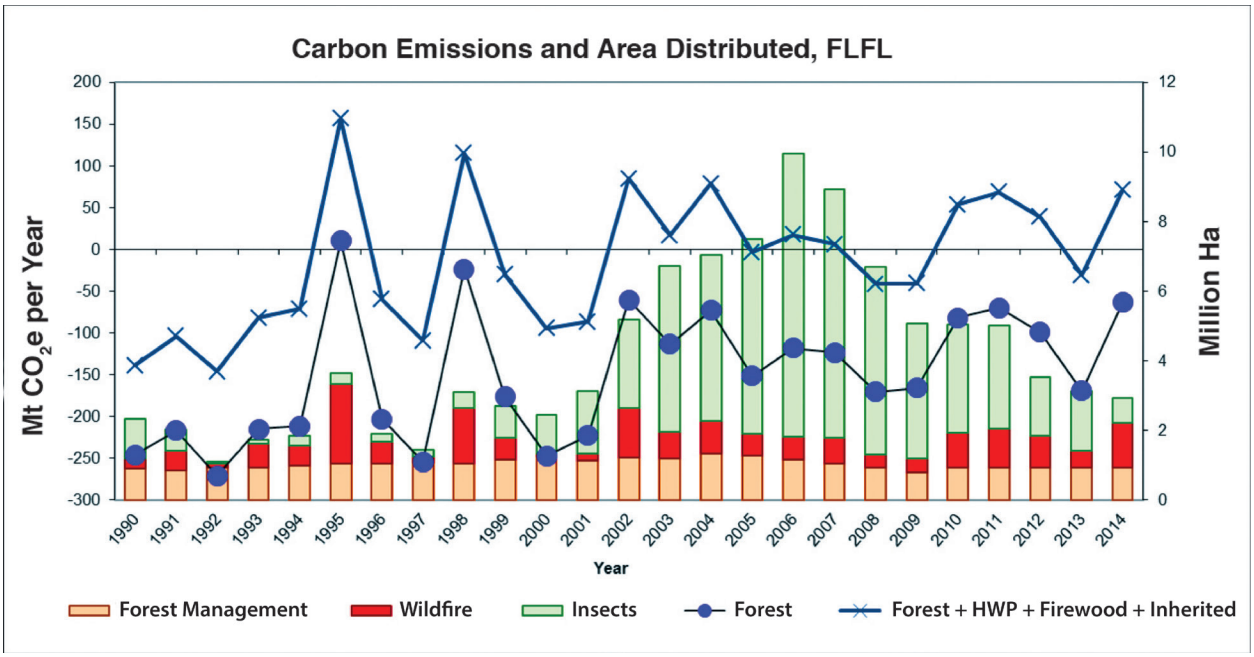


Figure 9.5. Effects of Natural Disturbances on Carbon Dynamics in Canada's Managed Forests. Disturbances such as wildfire and insects contribute to very large interannual variability in greenhouse gas (GHG) emissions and removals on the hectares (ha) of Canadian forestland remaining forestland (FLFL). Emissions include carbon dioxide (CO_2) and non-CO_2 GHGs converted to CO_2 equivalents (CO_2e). Forest fluxes are exchanges with the atmosphere, not counting the lateral transfer of harvested wood to the products sector. The upper line includes the forest carbon sink plus annual emissions from the harvested wood products sector, including firewood burning and annual emissions from wood harvested since 1941, regardless of where the wood was oxidized. [Figure sources: Adapted from ECCC 2016 and Stinson et al., 2011, used with permission.]

Climate change defines complex and uncertain adjustments to net carbon accumulation in forests. Several studies suggest that atmospheric enrichment from CO_2 and nitrogen could increase biomass growth by 0% to 2% annually (Fang et al., 2014; Schimel 2007; Shevliakova et al., 2013). Meanwhile, climate change generally is expected to increase the frequency and severity of natural disturbances in North America in the coming decades, potentially reducing forest carbon stocks considerably (Peterson et al., 2014; U.S. Forest Service 2012). Other climate change impacts—including shifts in growing season length, water availability, and temperature—will interact with atmospheric changes to determine forest growth responses (Gedalof and Berg 2010; McCarthy et al., 2006). Projection experiments that include a trend of increased productivity (+0.4%), coupled with forest age, disturbance, and management dynamics, indicate some potential for additional carbon uptake over baseline levels described previously (+5.1% from 2015 to 2050; Wear and Coulston 2015). However, increases are small relative to the projected changes for all other driving variables. Forest sink strength is likely to diminish gradually over the next 20 years as forest area gains tail off and forests continue to age. Uncertainty regarding the future carbon balance of North American forests increases with time. There is some potential for enhanced productivity resulting in a larger carbon sink, but disturbance rates and other elements of global change could increase carbon emissions from forests (Kurz et al., 2013; Lemprière et al., 2008). Uncertainties about the impacts of global change remain high. Increased sinks are unlikely to be of sufficient magnitude to offset higher emissions from increased disturbances

and enhanced release of carbon from decomposition (Kurz et al., 2013). However, the forest sink in the eastern temperate zone of North America is expected to be relatively stable despite these pressures (Wear and Coulston 2015).

9.5 Global Perspective

The North American forest carbon sink of 217 Tg C reported in this chapter represents about 20% of the global net forest carbon sink (Pan et al., 2011) on forest area that is 18% of the global total (FAO 2016b). Most of the North American carbon sink is in temperate U.S. forests that are managed relatively intensively for wood products and other services, indicating that managed forests typically are maintained with a lower stand density and lower carbon stocks than mature forests but have potentially higher growth rates. Current carbon stocks of North American forests average 155.4 Mg C per hectare, which is about 69% of the average for global forests (Pan et al., 2011), indicating higher-than-average carbon uptake and substantial capacity to increase average carbon stocks. According to the most comprehensive global estimates (FAO 2016a; Nabuurs et al., 2007), the mitigation potential of North American forests represents about 15% of the global forest mitigation potential for forestry activities according to "bottom-up" studies, sufficient to offset 2% of global CO_2 emissions (Le Quéré et al., 2015). The main mitigation activities for North American forests include reducing deforestation, increasing afforestation, and improving forest management—activities that are most viable in tropical and temperate biomes (FAO 2016a; Nabuurs et al., 2007).

9.6 Societal Drivers and Impacts

Atmospheric CO_2 uptake in U.S. forests has partially offset carbon emissions in other sectors of the U.S. economy. The 2014 net uptake estimate from forestland remaining forestland was 742 Tg CO_2e per year, which offset about 11% of gross U.S. GHG emissions. Assuming no policy intervention, the U.S. Department of Agriculture (USDA) reference scenario developed for the 2016 U.S. Biennial Report (USDA-OCE 2016) projects that annual carbon uptake will decrease to 320 Tg CO_2e per year in 2050 as a result of forest aging, forest disturbance, and land-use change.

Government policies to boost forest carbon uptake have the potential to slow its projected decline. Available options include altering (e.g., slowing, intensifying, or redirecting) development and increasing afforestation of private land in the eastern United States (12 million ha) and reforestation of public land in the western United States (5 million ha) to achieve no net loss of forest area beginning in 2025. Relative to the reference scenario, this option is projected to increase cumulative carbon uptake by 26% from 2015 to 2060 (USDA-OCE 2016).

One way to estimate the societal impact of policy options to increase forest carbon uptake is to estimate the benefit in terms of avoided damages resulting from a net carbon emissions reduction. This benefit is estimated using social cost of carbon (SCC) estimates, which are dollar estimates of the long-term damage done by a ton of CO_2 emissions in a given year. One report indicates that the SCC would increase from $42 in 2015 per 0.9 Mg CO_2e emitted to $80 in 2050, which can be translated to equivalent savings for uptake of CO_2e (using an average annual discount rate of 3%, with values in 2016 U.S. dollars; U.S. Interagency Working Group on Social Cost of Carbon 2013). As an example of the potential benefit of exploring policy options to boost forest carbon uptake, the current value of increased forest carbon uptake under a policy that reduces land development and increases afforestation and reforestation relative to the reference scenario is $132 billion (Bluffstone et al., 2017).

A policy option that involves afforestation of private forestland to increase forest carbon uptake could be achieved with incentives to private landowners. The USDA has five voluntary incentive programs, which account for more than 95% of USDA conservation spending (USDA-ERS 2014). When estimating benefits of incentive programs to increase forest carbon uptake, problems of "additionality" and "leakage" may lead to overestimating carbon uptake

gains (Lubowski et al., 2006). Estimates of forest carbon uptake by voluntary incentives may not be fully additional because some of this carbon would have been taken up on private forestland without the program. Furthermore, leakage could occur if landowners clear forestland for farming to compensate for land enrolled in the incentive program. Both additionality and leakage need to be accounted for when estimating the benefits of incentive programs to increase carbon uptake on private forestlands.

9.7 Carbon Management

Forest management activities have the potential to sustain and enhance the role of the North American forest sector in mitigating rising GHG concentrations over the next century. Key opportunities include 1) avoided deforestation emissions, 2) carbon uptake with afforestation and management to enhance stock growth, and 3) harvest removals directed toward clean energy options, including using logging residues and waste wood as a substitute for fossil fuels and long-lived wood products to replace building materials such as cement and steel that are more carbon emissions intensive (Birdsey et al., 2006; Lemprière et al., 2013).

Slowing deforestation and targeting clearings toward lands with lower carbon density could reduce carbon emissions substantially (Lemprière et al., 2013). Reducing harvest intensity, lengthening harvest rotations, and increasing stand densities are additional leading options because they generally increase carbon stocks in the absence of severe disturbance (Creutzburg et al., 2017; D'Amato et al., 2011; Harmon and Marks 2002; Perez-Garcia et al., 2007; Taylor et al., 2008). McKinley et al. (2011) reported that a combination of longer harvest intervals, management to increase vegetation growth rates, and establishment of preserves may increase carbon uptake by 30 to 105 Tg C per year in the United States alone. Important to note, however, is that slowing deforestation and harvesting in one region may simply displace such activities (i.e., leakage) if unmatched by a change in the demand for associated land uses and forest products. Moreover, increased carbon stocks in areas prone to severe disturbance may not act as a lasting sink for atmospheric carbon.

Forestry activities also may be adapted to promote soil carbon maintenance and transfer by minimizing disturbances to soil and stand structure and increasing forest productivity and the inputs to the soil (Canadell and Raupach 2008; Jandl et al., 2007). Other forestry efforts can minimize impacts to belowground carbon stocks associated with some management and harvesting activities (Nave et al., 2010; Noormets et al., 2015). Fuel reduction treatments that aim to lower severe fire risk may constitute a limited future sink for atmospheric carbon if expected future fire emissions could be reduced more than the carbon emissions from prescribed burning and mechanical removal (Hurteau and North 2009). Treatments that utilize wood removals for bioenergy may have additional mitigation benefits depending on the type of woody material used (harvest residues versus whole trees) and the fate of that material in the absence of fuel-reduction treatments (Dale et al., 2017). However, treatment areas tend to be much larger than the area they ultimately protect, so the net benefits over large landscapes may not be realized (Boer et al., 2015; Campbell et al., 2012; Hudiburg et al., 2013; Loehman et al., 2014).

Regarding afforestation, the potential for increasing carbon uptake in the United States alone is high, given that 1) the country's current forestland amounts to about 72% of that in 1630 (Smith et al., 2009) and 2) 60% of the CO_2 emitted from forest harvesting in the United States a century ago has yet to be resequestered (McKinley et al., 2011). U.S. afforestation alone could yield 1 to 225 Tg of additional forest carbon uptake per year in coming decades (McKinley et al., 2011). However, there are major practical limits to widespread implementation since the higher levels of afforestation would require taking land from other uses such as food production (Ray et al., 2009). In Canada, afforestation could add up to 59 Tg C per year (Lemprière et al., 2013). In Mexico, minimal data are available on the carbon

uptake potential of afforestation, or even forest management in general.

Another potential opportunity for reducing carbon emissions is shifting harvested wood from short-lived products toward uses with slower or no carbon release to the atmosphere (Bellassen and Luyssaert 2014; Lemprière et al., 2013; Oliver et al., 2014). An additional possibility is the use of forest biomass as a substitute for fossil fuels for energy production (Miner et al., 2014). Worth noting, however, is that long time frames, accurate counterfactuals, and full life cycle assessments often are needed to estimate the mitigation benefits of these and other carbon management activities, including bioenergy (Hudiburg et al., 2013; McKechnie et al., 2011; Perez-Garcia et al., 2007).

Estimates of the potential for forest management to mitigate rising GHGs vary widely because of uncertainties, mainly in natural disturbances, leakage effects, and carbon markets (Anderegg et al., 2015b; ECCC 2016; Gough et al., 2016; Harmon et al., 2011). Climate change effects are also uncertain and differ by forest type and location, making climate-adaptive forest management increasingly important (Duveneck and Scheller 2015). Assessment of carbon management opportunities may need to include consideration of vulnerability to disturbances. For example, locating carbon uptake activities in low-disturbance environments may be appropriate, along with perhaps focusing carbon emission actions (e.g., harvesting and land clearings) in higher-disturbance environments.

In the future, forest carbon management likely will be a co-benefit of many other forest uses and values. Owners and managers may decide to maintain lower carbon stocks as a side effect of pursuing other values, such as promoting habitat for select wildlife and reducing risk of severe wildfires.

9.8 Synthesis, Knowledge Gaps, and Outlook

9.8.1 Synthesis

Net carbon uptake by North American forests is well documented. Its strength varies regionally, with about 80% of the North American forest sink for atmospheric carbon occurring within the United States. Attributing North America's forest carbon sink to drivers remains difficult. Forest regrowth following historical clearing plays a role, but studies also suggest sizeable contributions from growth enhancements such as CO_2 fertilization, nitrogen deposition, or climate trends supporting accelerated growth. Resolving each factor's contribution is a major challenge and critical for developing reliable predictions. Several factors driving this sink are expected to decline over coming decades, and an increasing rate of natural disturbance could further diminish current net carbon uptake in the near term, possibly giving way to increased net carbon uptake in the more distant future if forests fully recover from today's disturbance trends.

Intensive forestry in select regions causes large annual reductions in forest carbon stocks that are eventually compensated for by forest regrowth, often over decades, if biomass recovers to preharvest conditions. However, carbon releases from the associated decay of harvested wood products offset a substantial portion (about half) of the net carbon sink in North American forests. Recent trends in natural disturbance rates have diminished the strength of net forest carbon uptake across much of North America. Net loss of forest carbon stocks from land conversions also reduces sink strength across the continent, with carbon losses from forest conversion exceeding carbon gains from afforestation and reforestation.

9.8.2 Gaps

Forests across North America are quite diverse. Although much is known about this diversity, datasets are still needed to characterize forest conditions at the scale of disturbance and management units (e.g., stand scale, ~30 m × 30 m). Such data would provide managers with the information necessary to design and implement effective carbon policy and management aiming to increase carbon uptake or reduce emissions. Maps of site productivity, stand age, and biomass at a stand scale (e.g., 30 m) would be

particularly valuable, offering practical improvements to current assessment capabilities.

Remeasurement data on tree- and stand-scale carbon stocks—including standing dead and downed wood and soil carbon pools and their turnover rates—are needed to record contemporary rates of carbon accumulation, improve understanding of net carbon uptake drivers, and aid assessment frameworks and models required for prediction. Also needed are analyses of expected shifts in forest composition in response to trends in climate; atmospheric composition; disturbances; the establishment and spread of invasive and/or exotic insects, pathogens, and plants; and management to improve projections of future carbon dynamics beyond an assumption of steady forest compositions and static ecotones. Conclusive evaluation of the rate and magnitude of woody encroachment is still lacking. Delivery of forest carbon to wetlands and waterways via erosion and drainage also is poorly quantified, despite its importance for continental-scale carbon budgeting and management.

Basic understanding of carbon flux and stock dynamics following disturbance is still limited, with some studies suggesting a substantial impact to fluxes (Edburg et al., 2011) and other studies reporting a more muted response (Moore et al., 2013; Reed et al., 2014). Predictions of future disturbance trends are hampered by limited understanding of disturbance interactions involving legacies of flammability and host species presence and absence, as well as active management responses such as fuel reduction treatments or preemptive and salvage logging. Also needed is knowledge of how belowground carbon stocks change as lands transition across uses over time (Domke et al., 2016). These gaps challenge assessments of legacy emissions and post-disturbance recovery and hamper attempts to quantify the potential of management activities to promote long-lived forest carbon sinks and reduce carbon emissions.

The use of remote sensing (e.g., Landsat) has led to major advances over the past decade in monitoring aspects of disturbance and land-use change (Bachelet et al., 2015; Hansen et al., 2013), but major research gaps remain. Disturbance histories at the stand scale and attribution to disturbance type and severity remain poorly characterized, as are rates of forest conversion. Improved estimates of the location, severity, and timing of natural disturbances are needed, particularly in Mexico. Degradation of forest stocks (e.g., from selective logging, low-severity disturbances, and stress) also remain poorly characterized at the scales needed for assessing carbon dynamics and managing forest carbon. Landscape-scale records of management practices such as replanting, selective harvesting, cyclical use, and agroforestry also are needed. Integration of a range of remote-sensing technologies, including light detection and ranging (LIDAR), with field plot data and carbon cycle modeling, promises to substantially improve the ability to measure and monitor forest carbon dynamics at large scales. Addressing these and other gaps ultimately will lead to spatially explicit estimates of carbon stocks and fluxes that comprehensively assess impacts of disturbance, management, and environmental changes on carbon fluxes.

Coupled experiments and models as well as multifactor manipulations are needed to better understand carbon cycling in forest ecosystems and the drivers contributing to carbon dynamics. Full life cycle analyses are required to improve understanding of today's carbon sinks in a longer temporal context, account for the full effects of management and global change drivers, and evaluate the costs and benefits of substituting wood products for other building materials or energy sources. Also needed is better information on the origin and fate of harvested wood products, which should enable more accurate and comprehensive estimation of harvesting impacts.

Collectively, the large uncertainties and substantial variation in model predictions and GHG inventory estimates can be attributed to the gaps identified in this section. Future assessments should attempt to better integrate data sources and products and

move beyond a focus on forest carbon exchange with the atmosphere toward full climate impact assessment such as in Anderson-Teixeira et al. (2012). Considerations are needed of 1) albedo changes from forest change, 2) CH_4 and N_2O fluxes, and 3) dynamics of other radiatively active atmospheric constituents such as aerosols and black carbon.

Also needed are management and planning tools (e.g., see Figure 9.6, this page) designed to help develop and evaluate alternative landscape-scale strategies for managing forests to address a range of ecosystem services including carbon. Platforms, such as the Forest Vegetation Simulator (FVS; www.fs.fed.us/fmsc/fvs/) and i-Tree (www.itreetools.org), enable assessment of impacts from disturbance trends and management scenarios in the context of uncertain global environmental changes to inform policymakers, land managers, industry, and the public. Such platforms can be designed to consider a wide range of ecosystem values beyond carbon to assess full climate forcing (i.e., albedo impacts), as well as biodiversity, habitat, water quality and quantity, timber production, disturbance avoidance, and other goods and services. Moreover, these platforms can be designed to flexibly handle uncertainty in forest responses to changes in climate and interactive trends in management and natural disturbance regimes.

9.8.3 Outlook

Climate change is influencing forest carbon in diverse ways, supporting enhanced carbon uptake in some regions by lengthening growing seasons and elevating CO_2 supply to photosynthesis. However, climate change also is leading to plant stress that reduces growth, increases the likelihood of mortality, and supports more extensive and severe disturbance-induced releases of carbon. All these drivers are altering the ecology and natural resources of North America's forests. How these processes and

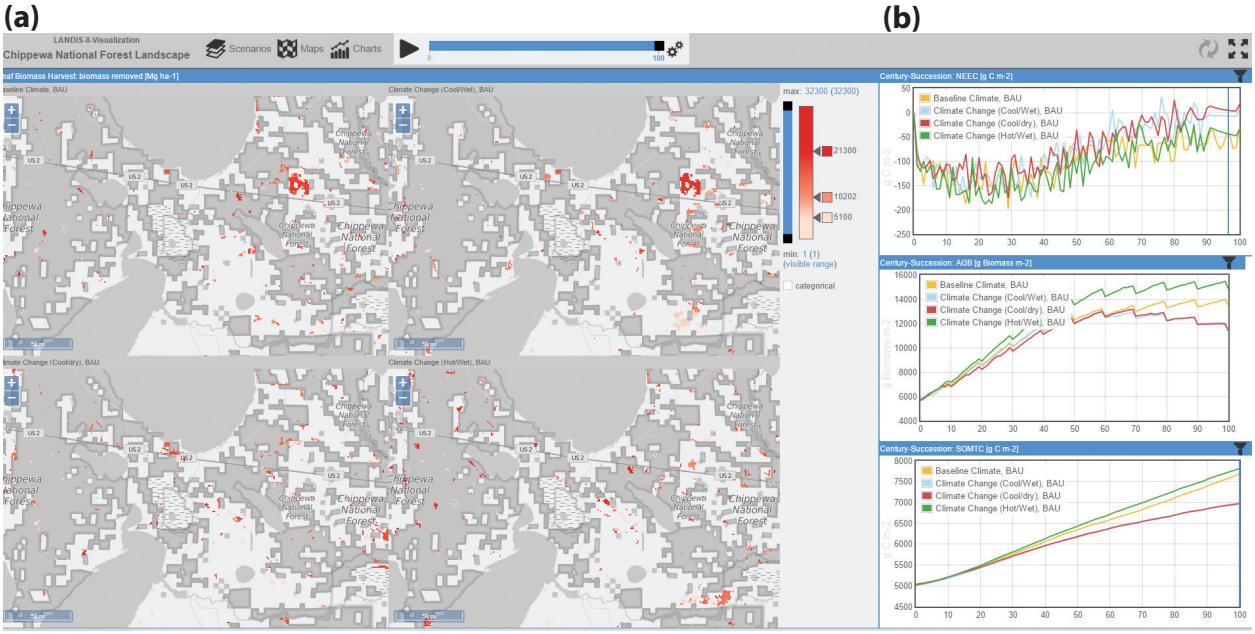


Figure 9.6. LandViz: A Forest Management and Planning Tool. LandViz maps and charts are generated for harvested timber **(a)** and carbon uptake rates, aboveground biomass, and soil carbon **(b)** using a forest simulation model (LANDIS-II) under historic climate and three climate change scenarios. LandViz is a visualization tool designed for forest managers to facilitate the integration of climate change results into the forest planning process. [Figure source: LandViz, Gustafson et al., 2016.]

their net effect will unfold over coming decades remains unclear.

Harvesting is the dominant forest management activity affecting carbon dynamics in North American forests; it has a net effect of reducing land carbon stocks and emitting carbon to the atmosphere. Slowing harvesting rates or modifying cutting practices could affect future forest carbon stocks significantly.

Several management activities could increase forest uptake of atmospheric carbon and decrease emissions in the forest sector (Birdsey et al., 2006; McKinley et al., 2011; Post et al., 2012). These activities include delaying or avoiding emissions from wood products by producing renewable building materials and developing energy sources with lower life cycle emissions than their GHG-intensive alternatives. Management through afforestation also may promote rapid regrowth of carbon stocks within forests (Erb et al., 2013) and even expand forestlands (Birdsey et al., 2006). However, practical limits are likely to severely constrain implementation, along with competition with other management and use objectives (Ray et al., 2009). Although climate mitigation activities, and associated carbon markets, remain highly uncertain, they clearly have the potential to substantially influence the priority placed on forest management to promote forest sector carbon storage.

SUPPORTING EVIDENCE

KEY FINDING 1

Net uptake of 217 teragrams of carbon (Tg C) per year by the forest sector in North America is well documented and has persisted at about this level over the last decade. The strength of net carbon uptake varies regionally, with about 80% of the North American forest carbon sink occurring within the United States (*high confidence, very likely*).

Description of evidence base

Net carbon uptake in North American forests, as documented in national inventory reports from Canada (ECCC 2016), Mexico (INECC/SEMARNAT 2015), and the United States (U.S. EPA 2018), is in broad agreement with results from a wide range of sources (Hayes et al., 2012; King et al., 2015). These sources include atmospheric inversion models (Peylin et al., 2013), syntheses of forest inventory and land-change data (Pan et al., 2011), measurements of forest-atmosphere carbon exchange with eddy covariance (Amiro et al., 2010), and ecosystem process models (Sitch et al., 2015).

Major uncertainties

Regions differ widely in their source and sink patterns and drivers. For example, in the United States, the Northeast has a prevailing legacy of carbon uptake from historical land clearing; in the Southeast, carbon uptake is dominated by regrowth from contemporary harvesting; and the West has increasing carbon releases from the recent rise in environmental stresses (e.g., droughts, insects, and pathogens) and disturbances (Williams et al., 2016). Fluxes also exhibit large spatial variability at landscape scales (Turner et al., 2016; Williams et al., 2014), with neighboring stands ranging from sources to sinks because of a host of factors including time since disturbance, disturbance type and severity, forest type, local climate, site fertility, topographic position, and other edaphic factors.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

While some uncertainty remains about the spatial patterns and drivers of carbon sources and sinks across the continent, multiple lines of evidence converge to provide high confidence regarding the magnitude of net carbon uptake across North America's forests in recent decades.

Summary sentence or paragraph that integrates the above information

It is highly likely that North American forests represent a net sink of carbon, given the convergence in evidence across multiple inventory, scaling, and modeling approaches in Canada, Mexico, and the United States.

KEY FINDING 2

Forest regrowth following historical clearing plays a substantial role in determining the size of the forest carbon sink, but studies also suggest sizeable contributions from growth enhancements such as carbon dioxide (CO_2) fertilization, nitrogen deposition, or climate trends supporting accelerated growth (*medium confidence*). Resolving each factor's contribution is a major challenge and critical for developing reliable predictions.

Description of evidence base

Although the use of remote sensing (e.g., Landsat) has led to major advances over the past decade in monitoring aspects of disturbance and land-use change (Bachelet et al., 2015; Hansen et al., 2013), critical research gaps remain. Disturbance histories at the stand scale and attribution to disturbance type and severity remain poorly characterized, as are rates of forest conversion.

Major uncertainties

Improved estimates of the location, severity, and timing of natural disturbances are needed, particularly in Mexico. Degradation of forest stocks (e.g., from selective logging, low-severity disturbances, and stress) also remain poorly characterized at the scales needed for assessing carbon dynamics and managing forest carbon. Also needed are landscape-scale records of management practices such as replanting, selective harvesting, cyclical use, and agroforestry. Integration of a range of remote-sensing technologies, including light detection and ranging (LIDAR), with field plot data and carbon cycle modeling, promises to substantially improve the ability to measure and monitor forest carbon dynamics at large scales. Addressing these and other gaps ultimately will lead to spatially explicit estimates of carbon stocks and fluxes that comprehensively assess impacts of disturbance, management, and environmental changes on carbon fluxes.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

While the evidence base strongly supports the finding of net carbon uptake by North American forests, attribution of this carbon uptake to driving factors remains less well understood. This is in part because each factor's contribution is likely to change across diverse forest settings and conditions.

Summary sentence or paragraph that integrates the above information

Attributing carbon fluxes in North American forests to specific natural and human activities remains a challenge given the diversity of forest types, land-use changes, disturbance dynamics, and human activities that influence these fluxes.

KEY FINDING 3

Annual harvest removals from forestry operations in select regions decrease forest carbon stocks, but this decline in stocks is balanced by post-harvest recovery and regrowth in forestlands that were harvested in prior years. Removal, processing, and use of harvested biomass causes carbon emissions outside of forests, offsetting a substantial portion (about half) of the net carbon sink in North American forests (*high confidence*).

Description of evidence base

Recent trends in natural disturbance rates indicate that the strength of net forest uptake has diminished across much of North America. Net loss of forest carbon stocks from land conversions also reduces sink strength across the continent, with carbon losses from forest conversion exceeding carbon gains from afforestation and reforestation. These findings are supported by 1) national inventory reports of greenhouse gas emissions and removals in the forestland category in Canada (ECCC 2016), Mexico (INECC/SEMARNAT 2015), and the United States (U.S. EPA 2018); 2) atmospheric inversion models (Peylin et al., 2013); 3) syntheses of forest inventory and land-change data (Pan et al., 2011); 4) measurements of forest-atmosphere carbon exchange with eddy covariance (Amiro et al., 2010); and 5) ecosystem process models (Sitch et al., 2015).

Major uncertainties

Intensively managed forests are among the most well understood ecosystems in North America. Decomposition dynamics associated with harvested wood products are less well understood, however, and changes in forest use and climate may alter these dynamics in the future. Furthermore, basic understanding of carbon flux and stock dynamics following disturbance is still limited, with some studies suggesting a substantial impact to fluxes (Edburg et al., 2011) and others reporting a more muted response (Moore et al., 2013; Reed et al., 2014). Predictions of future disturbance trends are hampered by limited understanding of disturbance interactions from legacies of flammability, host species presence and absence, and active management responses such as fuel reduction treatments or preemptive and salvage logging.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

The carbon balance impacts of harvesting are well observed and well understood thanks to a wide range of observations that are compiled, analyzed, and reported in detailed accounts.

Summary sentence or paragraph that integrates the above information

Intensive forest management in select regions is widely known to cause large annual reductions in forest carbon stocks. Less understood is how forest regrowth (which often takes decades) compensates for these losses.

KEY FINDING 4

Recent trends in some disturbance rates (e.g., wildfires and insects) have diminished the strength of net forest carbon uptake across much of North America. Net loss of forest carbon stocks from land conversions reduced sink strength across the continent by 11 Tg C per year, with carbon losses from forest conversion exceeding carbon gains from afforestation and reforestation (*medium confidence*).

Description of evidence base

Carbon impacts of disturbance vary with several key features, including disturbance type and severity, temporal sequence of events, and biotic and climatic conditions of forest regeneration (Hicke et al., 2012; Williams et al., 2016). The extent, severity, and frequency of natural disturbances have increased in recent decades (Allen et al., 2010; Hicke et al., 2013), likely influenced by recent climate change and human activities.

Major uncertainties

Basic understanding of carbon flux and stock dynamics following disturbance is still limited, with some studies suggesting a substantial impact to fluxes (Edburg et al., 2011) and others reporting a more muted response (Moore et al., 2013; Reed et al., 2014). Predictions of future disturbance trends are hampered by limited understanding of disturbance interactions from legacies of flammability, host species presence and absence, and active management responses such as fuel reduction treatments or preemptive and salvage logging.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Patterns and trends of major disturbances and forest conversions are well documented, however, their effects on carbon uptake and release can be diverse, presenting a significant challenge for assessing impacts on the carbon cycle.

Summary sentence or paragraph that integrates the above information

Detection and quantification of natural disturbance and land-use change in forest ecosystems have improved over the last decade. However, basic understanding of carbon dynamics following these events is still limited. Nevertheless, evidence suggests that recent trends in natural disturbance rates have diminished the strength of net forest uptake across much of North America.

KEY FINDING 5

Several factors driving the carbon sink in North American forests are expected to decline over coming decades, and an increasing rate of natural disturbance could further diminish current net carbon uptake (*medium confidence*).

Description of evidence base

Accounting for land-use change, management, disturbance, and forest aging, U.S. forests are projected to continue to uptake carbon but at declining rates, largely because of land-use dynamics and aging forests (USDA-OCE 2016; Wear and Coulston 2015). After 20 years of net gains, forest area is projected to level and then decline gradually after 2030 because of ongoing population growth and declining afforestation on agricultural lands (U.S. Forest Service 2012; Wear and Coulston 2015). In the western United States, aging forests coupled with disturbance dynamics are projected to diminish carbon uptake to negligible levels by midcentury. Younger productive forests in the East are expected to take up atmospheric carbon at a high rate, though harvest-related emissions substantially reduce the net effect on atmospheric carbon.

Major uncertainties

Basic understanding of carbon flux and stock dynamics following disturbance is still limited, with some studies suggesting a substantial impact to fluxes (Edburg et al., 2011) and others reporting a more muted response (Moore et al., 2013; Reed et al., 2014). Predicting disturbance trends into the future is challenging because of limited understanding of disturbance interactions from legacies of flammability, host species presence and absence, and active management responses such as fuel reduction treatments or preemptive and salvage logging. Forest regrowth following historical clearing plays a role, but studies also suggest sizeable contributions from growth enhancements such as CO_2 fertilization, nitrogen deposition, or climate trends supporting accelerated growth. Resolving each factor's contribution is a major challenge and critical for developing reliable predictions.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Although projections vary depending on future climate and land-use scenarios, theory, observations, and modeling all support the expectation that today's carbon uptake from aging forests and from forest expansion will begin to decline in coming decades, and that natural disturbances will become more frequent and severe, releasing more forest carbon to the atmosphere.

Summary sentence or paragraph that integrates the above information

Although detection and quantification of natural disturbance and land-use change in forest ecosystems have improved over the last decade, basic understanding of carbon dynamics following these events is still limited. Several factors driving the forest carbon sink are expected to decline over coming decades, and although predicting disturbance trends into the future is challenging, an increasing rate of natural disturbance could further diminish the current estimated net carbon uptake by North American forests.

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10 Grasslands

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KEY FINDINGS

1. Total grassland carbon stocks in the conterminous United States, estimated to be about 7.4 petagrams of carbon (Pg C) in 2005, are projected to increase to about 8.2 Pg C by 2050. Although U.S. grasslands are expected to remain carbon sinks over this period, the uptake rate is projected to decline by about half. In the U.S. Great Plains, land-use and land-cover changes are expected to cause much of the change in carbon cycling as grasslands are converted to agricultural lands or to woody biomes (*medium confidence*).

2. Increasing temperatures and rising atmospheric carbon dioxide (CO_2) concentrations interact to increase productivity in northern North American grasslands, but this productivity response will be mediated by variable precipitation, soil moisture, and nutrient availability (*high confidence, very likely*).

3. Soil carbon in grasslands is likely to be moderately responsive to changes in climate over the next several decades. Field experiments in grasslands suggest that altered precipitation can increase soil carbon, while warming and elevated CO_2 may have only minimal effects despite altered productivity (*medium confidence, likely*).

4. Carbon stocks and net carbon uptake in grasslands can be maintained with appropriate land management including moderate levels of grazing. Fire suppression can lead to encroachment of woody vegetation and increasing carbon storage in mesic regions, at the expense of grassland vegetation (*high confidence, likely*).

Note: Confidence levels are provided as appropriate for quantitative, but not qualitative, Key Findings and statements.

10.1 Carbon Cycling in Grasslands

Grasslands cover 30% of North America and provide a wealth of essential ecosystem services, such as wildlife habitat, hydrological buffering, soil stabilization, carbon storage, and forage production. Grassland ecosystems are characterized by herbaceous vegetation, including grasses and nongrass species, with a minor component of woody vegetation in most regions. Most grasslands in North America are dominated by perennial vegetation, or species that continue growing for many years, although in parts of California and the Intermountain West, nonnative annual grasses now dominate. Grasses allocate 40% to 80% of net primary production (NPP) to roots (Hui and Jackson 2006), so most carbon storage takes place below ground (Silver et al., 2010; Smith et al., 2008; Soussana et al., 2004). Grasslands across North America occupy over 7 million km^2 (see Table 10.1, p. 401) and contain 10 to 90 megagrams of carbon (Mg C) per hectare in the top 20 cm of soil (Burke et al., 1989; Potter and Derner 2006; Silver et al., 2010).

Carbon storage, defined as the net uptake of carbon by a given pool or reservoir (IPCC 2013), can be quantified as the change in stocks measured over time, or as annual net ecosystem production (NEP), which can be measured as NPP minus losses from soil organic matter (SOM) decomposition (Chapin et al., 2006). NEP is also estimated from the sum of high-frequency net carbon dioxide (CO_2) exchange (NEE) measurements from eddy covariance "flux tower" methods. By contrast, net ecosystem carbon balance (NECB) accounts for all carbon uptake and loss processes, including harvest, natural disturbance, leaching, and trace gas species in addition to CO_2 (Chapin et al., 2006).

This chapter is relevant to both the Northern and Southern Plains National Climate Assessment regions, as well as the Southwest and Midwest regions. The spatial scope of this chapter encompasses the major North American grassland regions, which can be defined by climatic limitations. Grasslands occur where potential evaporation exceeds

Table 10.1. Average Modeled Net Ecosystem Production (In Tg C per Year During 2000 to 2006)

Country	Approximate Grassland Area (km^2)[a]	Inventory Analysis[b, c]	Atmospheric Inversion Models[c, d]	Land-Surface Models[c, d]
Canada	3,920,000	–3.06	–51.2	–29.3
United States	2,580,000	–13.2	–266.2	–104.8
Mexico	760,000	–9.06	–15.1	+3.6
North America	7,260,000	–25.2	–332.5	–130.5

This table, adapted from Hayes et al. (2012), presents three different approaches for estimating net ecosystem production (NEP): inventory analysis, atmospheric inversion models, and land-surface models.

Notes

a) Approximate grassland area is derived from www.statista.com/statistics/201761/projection-for-total-us-grassland-area-from-2010.

b) Inventory analysis estimates, in teragrams of carbon (Tg C) per year, are the sum of livestock methane (CH_4) emissions, livestock carbon dioxide (CO_2) emissions, and grassland net ecosystem exchange (NEE) for Canada and the United States. For Mexico, the NEP value for "Others" was used from Table S10 in Hayes et al. (2012).

c) A negative flux represents net ecosystem carbon uptake, while a positive flux indicates carbon loss from the ecosystem.

d) Atmospheric inversion models and land-surface models are from Table 2 in Hayes et al. (2012) and exclude CH_4 emissions and human settlement emissions.

precipitation, such as in central North America from Canada through Mexico and in mountain rain shadows in the western United States (Sims and Risser 2000). They also occur in more mesic (wet) regions where disturbance, management, or soil conditions prevent woody growth, such as in central Florida (Stephenson 2011). North American grasslands generally increase in productivity and carbon storage as precipitation increases, from west to east (Sims and Risser 2000). This pattern is observed in Canada and to a lesser extent in Mexico. Mixed-grass prairie is extensive in south-central Canada, while more arid desert grassland and shortgrass steppe extend through the southwestern United States into Mexico (Sims and Risser 2000). Grasslands at the more arid extreme are considered more vulnerable to diminished productivity in a future warmer climate (Hufkens et al., 2016), whereas grasslands in more mesic climates may be vulnerable to woody encroachment (Knapp et al., 2008a).

Land management strongly affects productivity and carbon cycling in grasslands (see Figure 10.1, p. 402). In the conterminous United States, grasslands, shrublands, rangelands, and pastures make up at least 40% of land cover (Reeves and Mitchell 2012; see Figure 10.1). Most areas of highly productive grasslands have been converted to agriculture (see Ch. 5: Agriculture, p. 229, for more details; Bachelet et al., 2017).

10.2 Current Understanding of Grassland Productivity and Carbon Stocks

10.2.1 Grassland Carbon Stocks and Fluxes

Key Finding 1 is based on estimates of carbon stocks and fluxes as determined by upscaling inventories with remote-sensing products and modeling approaches. This section of the chapter describes the current understanding of carbon stocks and fluxes, and later sections evaluate the processes responsible for changes in these pools and fluxes.

Continental Scale

Terrestrial biosphere models are important tools for understanding how the carbon cycle responds

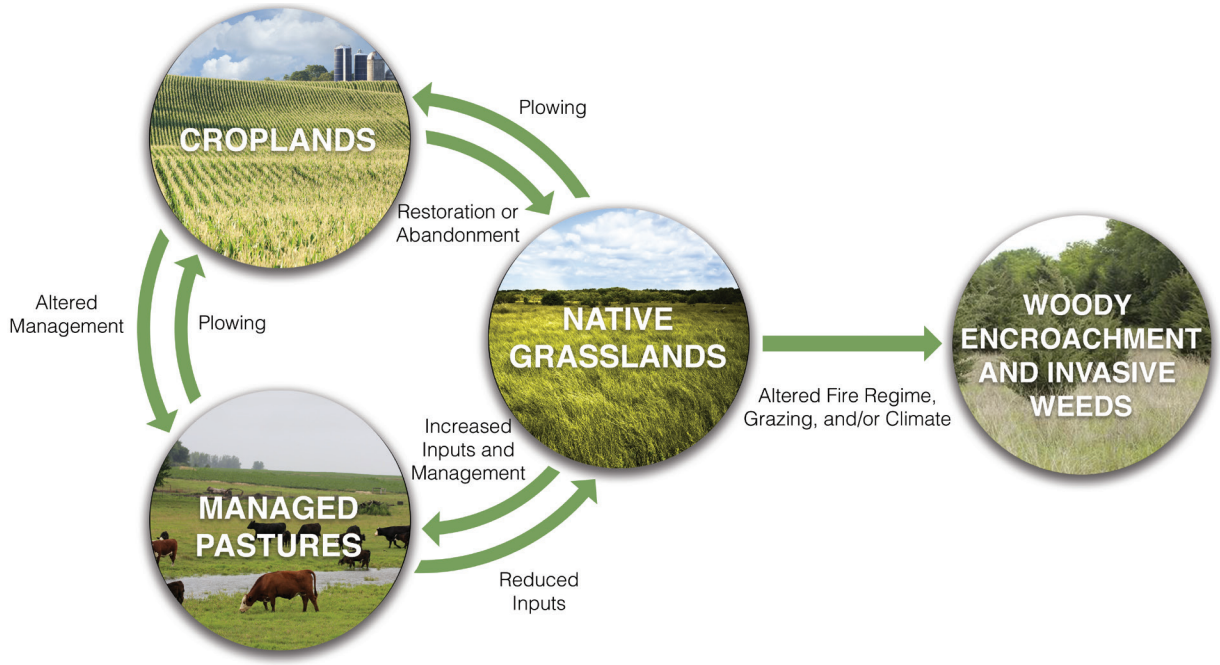

Figure 10.1. Management Activities and Their Effects on Grassland Carbon Cycling. Reduced fire frequency in mesic native grassland has allowed woody vegetation such as *Juniperus virginia* to expand and has been associated with rapid increases in carbon stocks in vegetation and soils (McKinley and Blair 2008). Other observed management impacts include lower carbon density in agricultural lands compared with grasslands (Zhu et al., 2011) and the rapid accumulation of soil carbon in intensively managed pastures in the southeastern United States (Machmuller et al., 2015). In addition, the rate of carbon uptake by croplands in the Great Plains is 30% lower than that of grasslands (Wylie et al., 2016).

to changes in climate, nutrient availability, and land use. Modeled rates of uptake or loss are dependent on a given region's processes and area. A multimodel synthesis study estimated that North American grassland acted as a carbon sink, with an average uptake rate of 38 grams of carbon (g C) per m^2 per year during the first 5 years of this century (Raczka et al., 2013). A similar synthesis of 17 land-surface models (LSMs) showed that North American grasslands acted as carbon sinks (see Table 10.1, p. 401) from 2000 to 2006 (Hayes et al., 2012). Atmospheric inversion models (AIMs) also predicted a carbon sink for North American grasslands but at a rate roughly twice the magnitude compared to that in land-surface models (see Table 10.1, p. 401; Hayes et al., 2012). At the national level, carbon sinks are proportional to the area in grasslands and reflect different management and climate conditions. U.S. grasslands contribute the continent's largest sink, followed by those in Canada, with Mexican grasslands approaching carbon-neutral status.

Similar to the modeled estimates, inventory analyses also suggest that Canadian and U.S. grasslands are carbon sinks (see Table 10.1, p. 401; Hayes et al., 2012). The differences in estimated carbon sink magnitude between these approaches could stem from estimating fluxes using changes in stocks (i.e., inventory methods) versus changes in atmospheric CO_2 concentrations (i.e., AIMs) or carbon cycle processes (i.e., LSMs), or from extrapolating fluxes over different land areas. Furthermore, most previous LSMs have not considered effects of land-use change and fire suppression, both which are implicit in AIM analyses. Inventories might miss these

Table 10.2. Carbon Fluxes and Stocks for Grasslands and Shrublands in the Conterminous United States (Summarized from the LandCarbon Project, landcarbon.org/categories)

	Time Period	Biomass[a]	Soil[b]	Other[c]	Total	Area (10^6 km^2)
Annual Flux (Tg C per Year)[d]						
	2000–2005	+7.2	–45.5	–16.3	–54.7	2.66
	2005–2050	+5.8	–20.1	–7.6	–21.8	2.51
Total Carbon Stock (Tg C)[d]						
	2005	1,362.1	5,090.4	958.6	7,411.1	2.66
	2050	1,090.4	6,021.8	1,072.3	8,184.5	2.51

Notes

a) Biomass includes aboveground and belowground live plant parts.

b) Soil stocks consider the top 20 cm.

c) Other includes leaf litter and woody debris.

d) Values, in teragrams of carbon (Tg C), are averages of the A1B, A2, and B1 climate scenarios and estimated using the FORE-casting SCEnarios of land-use change (FORE-SCE) model and the Erosion-Deposition-Carbon-Model (EDCM), CENTURY, and PBN carbon models (Liu et al., 2012b, 2014; Zhu et al., 2011). A negative carbon flux represents net ecosystem carbon uptake, while a positive carbon flux indicates carbon loss from the ecosystem.

effects if they consider only areas that remain as grasslands. Recent LSM simulations indicate that fire suppression reduces areal extent of grasslands in the conterminous United States and allows woody biomass to encroach (Bachelet et al., 2017). A recently developed remote-sensing method discovered 300% more burned areas in the Great Plains than did the previous method for the 1984 to 2013 period (Hawbaker 2017). These examples demonstrate that considering disturbance and land-use effects is key to reducing uncertainties in inventories and model projections of carbon cycling. Section 10.5, p. 415, discusses these societal impact questions in more detail.

Conterminous United States

Various efforts on scaling up flux tower observations and biogeochemical modeling mostly confirm that U.S. grasslands typically have been a carbon sink in recent years (Liu et al., 2012b, 2014; Xiao et al., 2014; Zhang et al., 2011; Zhu et al., 2011). By scaling up flux tower observations, Zhang et al. (2011) showed that the Great Plains, which makes up the majority of U.S. grasslands, was a net sink from 2000 to 2008, with an average net uptake of 24 ± 14 g C per m^2 per year (i.e., annual uptake varied from 0.3 to 47.7 g C per m^2 per year). The result was consistent with a similar study over North America that showed U.S. grasslands were a net carbon sink from 2001 to 2012 (Xiao et al., 2014). However, a recent biogeochemical modeling study suggested that U.S. grasslands during 2001 to 2005 lost 3 teragrams of carbon (Tg C) per year, amounting to about 120 g C per m^2 averaged over the conterminous United States (Wang et al., 2015). These contrasting results, along with the differences shown in Table 10.1, p. 401, indicate a discrepancy between modeling estimates and empirical, data-driven values that contribute to uncertainty in grassland carbon cycling rates.

The LandCarbon project (www2.usgs.gov/climate_landuse/land_carbon) provided a national ecosystem carbon sequestration assessment conducted by the U.S. Geological Survey (USGS) in response to requirements of the Energy Independence and Security Act of 2007 (EISA; H.R. 6 — 110th Congress 2007). The objective of the EISA assessment was to evaluate policy-relevant carbon sequestration capacity in terrestrial ecosystems through management or restoration activities. Climate, land-cover change, and fire disturbance were included in the carbon assessment. Grassland and shrubland assessments were combined for this chapter. U.S. national

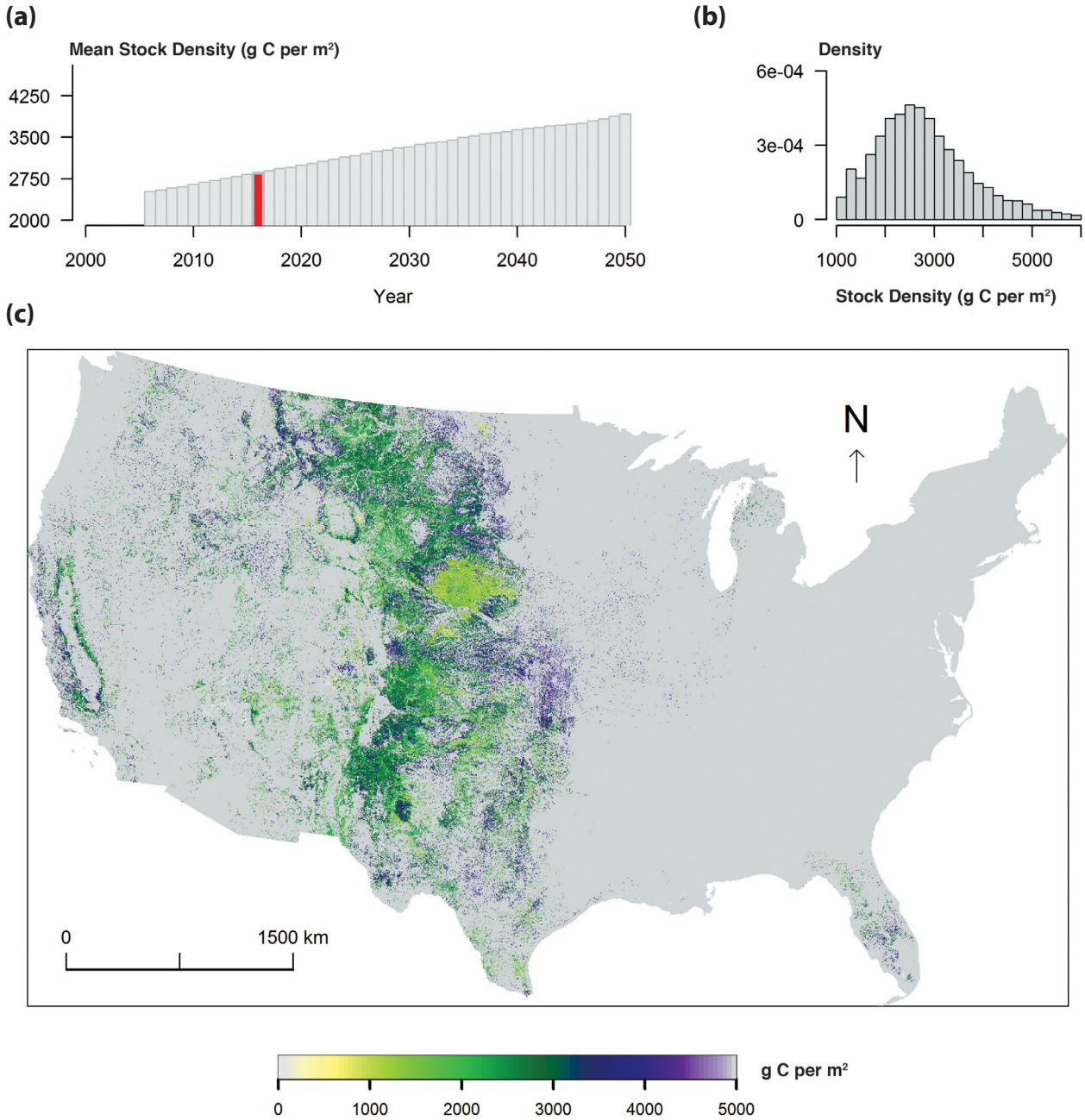

Figure 10.2. Model Simulation of Total Carbon Storage in U.S. Grasslands, 2016. (a) Spatial mean of carbon density in stocks over the 2005–2050 simulation period (red bar, 2016). **(b)** Number of pixels across the range of carbon density for 2016. **(c)** Total carbon storage in soils and vegetation for grasslands of the conterminous United States, simulated using the Erosion-Deposition-Carbon-Model (EDCM). Model simulations started in 1992 with initial soil carbon data from the Soil Survey Geographic database (SSURGO) and future climate projection from the Model for Interdisciplinary Research on Climate (MIROC; Liu et al., 2012a; Liu et al., 2014; Zhu et al., 2011). The Moderate Resolution Imaging Spectroradiometer (MODIS) net primary production products from 2001 to 2011 were used to constrain EDCM simulations, and the inverse model parameter values were used for future projections. Key: g C, grams of carbon.

summaries for 2001 to 2005 and 2006 to 2050 are shown in Table 10.2, p. 403, and Figure 10.2, p. 404. These projections represent simulation results using:

- Climate change data from the Model for Interdisciplinary Research on Climate (MIROC) general circulation model under three emissions scenarios (i.e., A1B, A2, and B1; IPCC 2000);
- Land-cover change data from the FOREcasting SCEnarios of land-use change (FORE-SCE) model (Sohl et al., 2007); and
- Three biogeochemistry models: Erosion-Deposition-Carbon Model (EDCM), CENTURY, and PBN (Liu et al., 2012b, 2014; Zhu et al., 2011).

Although the USGS LandCarbon Project currently does not include new representative concentration pathway (RCP) scenarios in its biological carbon sequestration assessment, the project considers climate projections for temperature and precipitation to be quite similar between the IPCC (2000) and RCP scenarios (Knutti and Sedláček 2013).

Figure 10.2 shows the estimated spatial pattern of carbon stocks in vegetation and soil in the top 20-cm layer in 2016 and the temporal change of the mean U.S. grassland carbon stock from 2005 to 2050 under the Intergovernmental Panel on Climate Change (IPCC) scenario A1B (IPCC 2000), estimated using the EDCM model (Liu et al., 2011, 2014; Zhu et al., 2011). More information about the methodology and results from other carbon models and scenarios can be found in a series of reports (Zhu and Reed 2012, 2014; Zhu et al., 2011) and the LandCarbon project (www2.usgs.gov/climate_landuse/land_carbon). The majority of U.S. grassland is distributed in the central Great Plains ecoregion, California, and central Florida, with large spatial variability in carbon stocks. At the U.S. national scale, the mean carbon stock was projected to increase over time (see Figure 10.2, p. 404).

The spatial distribution of the current decadal mean rate of the grassland NECB is shown in Figure 10.3, p. 406. The average annual carbon uptake varied from 15 to 40 g C per m^2 per year with a decreasing trend after 2030 under scenario A1B (see Figure 10.3, p. 406). Carbon stocks were projected to continue increasing until mid-century despite declining NECB. The clear spatial pattern of the carbon fluxes from 2007 to 2016 is characterized by 1) carbon-neutral status (e.g., the Nebraska Sandhills in the central United States), 2) carbon losses mostly in north-central United States, and 3) carbon uptake mostly in the midwestern United States and California. The carbon dynamics since 2005 were simulated using the MIROC climate projections. Consequently, the simulated NECB and its spatial pattern might be different from reality, especially in the severely drought impacted areas of California in recent years.

Regional Scale: Great Plains Ecoregion as a Case Study

The Great Plains, comprising 2.17 million km^2 are dominated by grasslands, interspersed with shrublands, that account for 48% of the total area, while agricultural lands cover 42% of the total area (Zhu et al., 2011; see Figure 10.4, p. 407). Zhang et al. (2011) integrated remotely sensed vegetation greenness and weather datasets from 2000 to 2008 with NEP data from 15 eddy covariance flux tower sites to scale up and calculate a carbon budget for the Great Plains biome. The entire Great Plains was shown to have an average (± standard deviation) uptake rate of 24 ± 14 g C per m^2 per year (i.e., a range of 0.3 to 47.7 g C per m^2 per year). While the carbon uptake by the Great Plains was lower in the dry years, the entire biome remained a net carbon sink in 8 of the 9 years (Zhang et al., 2011). This study illustrated that, despite significant interannual and spatial variation, mature native grasslands have the potential to sequester significant amounts of carbon for extended periods of time (see Figure 10.4, p. 407). A recent regression tree analysis based on remote-sensing and flux tower data estimated a spatially averaged annual uptake by grasslands of 45 g C per m^2 per year in the same period (Wylie et al., 2016), confirming previous findings that grasslands are resilient carbon sinks.

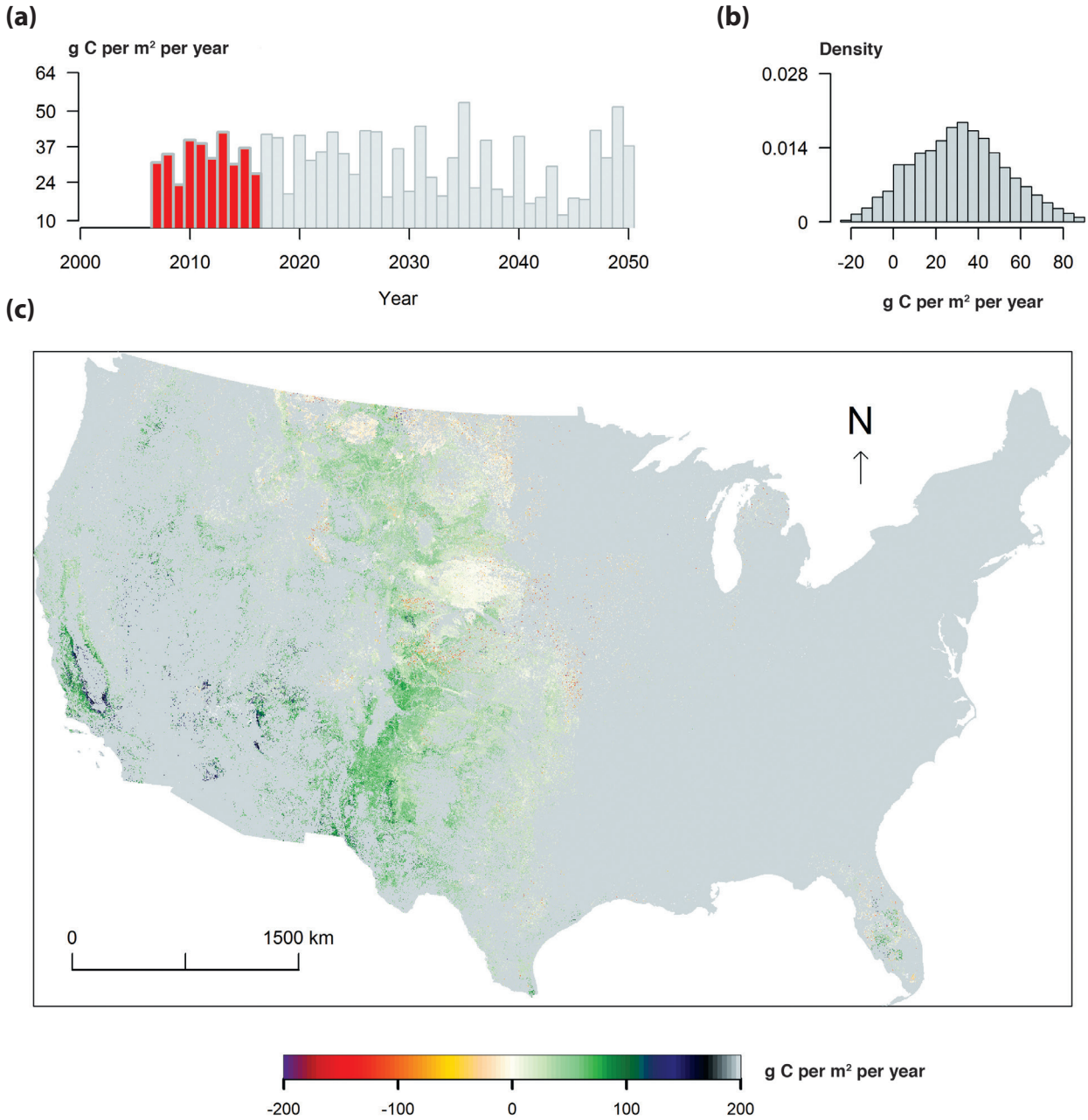

Figure 10.3. Model Simulation of Net Ecosystem Carbon Balance (NECB) for U.S. Grasslands in Response to Intergovernmental Panel on Climate Change Scenario A1B. (a) Spatial mean of NECB fluxes over the 2005–2050 simulation period (red bars, 2007–2016). Carbon increase rates are projected to decrease after 2030. **(b)** Probability of fluxes for the period 2007–2016. Positive and negative values indicate net input to and net loss from grasslands, respectively. **(c)** Spatial patterns of the decadal mean fluxes of NECB are shown from 2007 to 2016 (red portion in panel (a). Effects of climate and land-use change on NECB are combined in this simulation by the Erosion-Deposition-Carbon-Model (EDCM; Liu et al., 2014; Liu et al., 2012b; Zhu et al., 2011). Positive and negative values indicate net input to and net loss from grasslands, respectively. Key: g C, grams of carbon.

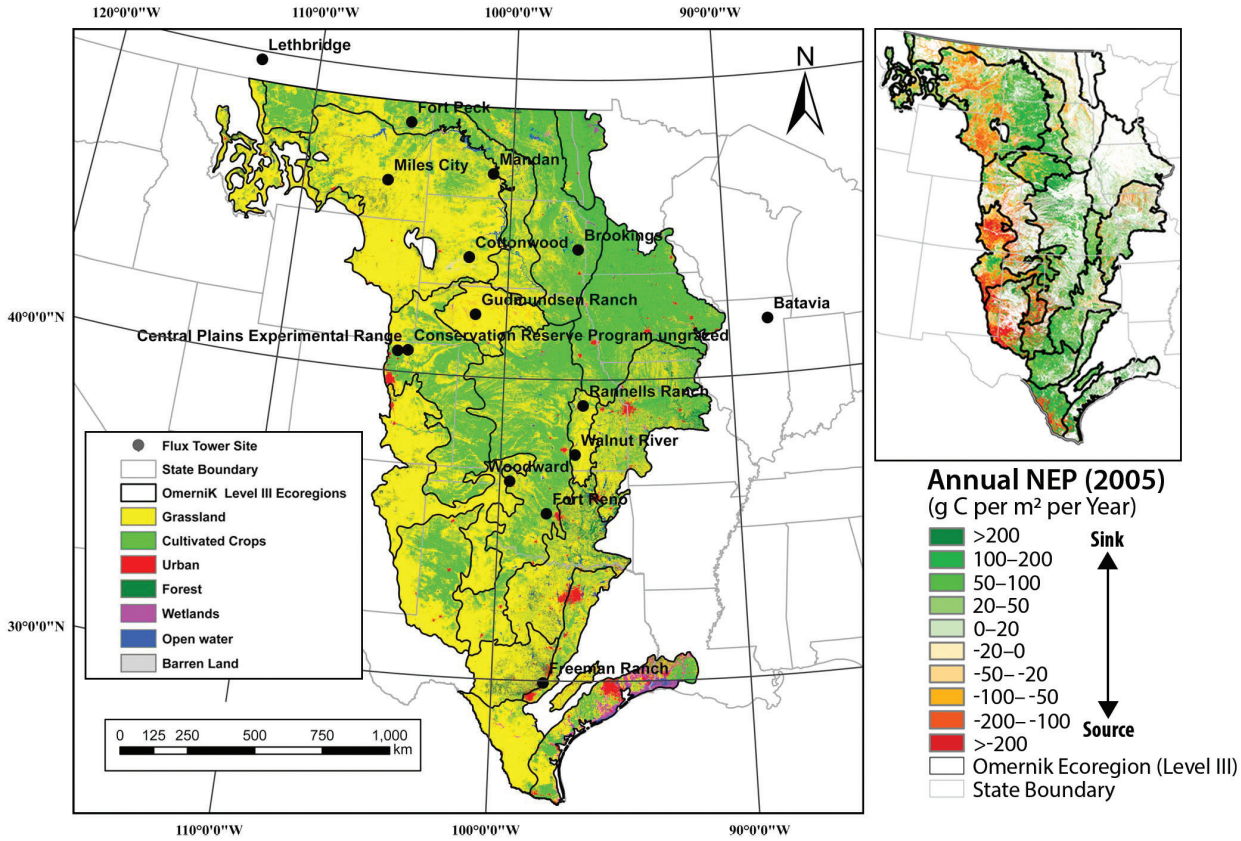

Figure 10.4. The Great Plains Ecoregion: Land Cover, Grassland Flux Towers, and Carbon Flux in 2005. The land-cover map for the Great Plains Ecoregion (Omernik 1987) was derived from the 2001 National Land Cover Database. The net ecosystem production (NEP) map was simulated based on land-cover type (Homer et al., 2004) and flux tower measurements using weather conditions for 2005. No fire disturbance or land-cover change effects were included. Key: g C, grams of carbon. [Figure source: Adapted from Zhang et al., 2011, used with permission.]

10.2.2 Processes Affecting Carbon Stocks and Fluxes in Grasslands

Climate Variability

Key Findings 2 and 3 relate to climate effects on grasslands, which will vary spatially and temporally. Grassland carbon balance is strongly sensitive to precipitation, often resulting in increased carbon losses in dry years or over drought-affected areas, particularly in the southwestern Great Plains (see Figure 10.4, this page; Biederman et al., 2016; Scott et al., 2015; Svejcar et al., 2008; Zhang et al., 2011). These frequent shifts from uptake to emissions in response to reduced precipitation indicate that grasslands are closer to the threshold for net carbon storage than are forests (Scott et al., 2015). This interannual variation in grassland NEP results from interactions between moisture and temperature controls on leaf area production, photosynthesis, and respiration (Flanagan and Adkinson 2011). If moisture is not limiting, carbon storage can increase significantly in response to warmer conditions and rising atmospheric CO_2 (see Section 10.3.3, p. 410). In part, this increase results from flexible timing of grassland plant growth and photosynthesis (Ryan et al., 2016; Zelikova et al., 2015). For example, drought decreased the growing season length and led to reductions in NPP and carbon sequestration in the Canadian Great Plains (Flanagan and Adkinson 2011).

Land-Use and Land-Cover Changes (Grazing and Species Shifts)

Key Finding 4 relates to management impacts on grassland carbon stocks and fluxes. A recent simulation suggests that Great Plains grassland area declined by 16% from 1992 to 2005 due to land-use change, including fire suppression (Bachelet et al., 2017). However, carbon stocks in remaining grasslands are considered to be stable or increasing (Zhu et al., 2011).

Grazing Effects on Grassland Carbon Cycling. Grasslands in North America evolved with native herbivores, historically grazed by livestock with varying intensities. Poor grazing management has been associated with reductions in productivity and soil carbon stocks, but improved management approaches, such as appropriate fertilization or reduced grazing intensity, can restore or even increase the original potential for carbon storage (Conant et al., 2001). Grazing intensity affects species composition and soil carbon content. For instance, heavy grazing can reduce aboveground productivity and root biomass, alter microbial community composition, and increase soil decomposition rates (Klumpp et al., 2009). However, intensive, early spring grazing may improve net carbon uptake by stimulating re-growth of plants later in the growing season, contingent on rainfall seasonality (Owensby et al., 2006; Svejcar et al., 2008). Some studies reported no effect of grazing on grassland carbon exchange (Polley et al., 2008; Risch and Frank 2006), and moderately grazed prairies can remain net carbon sinks (Frank 2004). In one recent study, moderate grazing was associated with average net carbon uptake of nearly 300 g per m^2 per year, but this was reduced to zero with heavy grazing (Morgan et al., 2016). Furthermore, low-precipitation years can reduce productivity in grazed ecosystems (Ingram et al., 2008; Polley et al., 2008), leading to net carbon losses in combination with heavy grazing (Morgan et al., 2016). In intensively managed, fertilized pastures on degraded former croplands in the mesic southeastern United States, soil carbon stocks returned to their preagricultural levels within about 6 years, because of high NPP and rapid belowground carbon cycling (Machmuller et al., 2015). In mesic Texas rangelands, adaptive management, using high stocking rates for short durations across multiple paddocks, increased soil carbon relative to continuous heavy grazing (Teague et al., 2011). These studies suggest that grassland carbon cycling is resilient to appropriately managed grazing (see Figure 10.1, p. 402). However, a global meta-analysis indicates that grazing impacts on carbon storage are contingent on many factors, including precipitation, soil texture, plant species competition, and grazing intensity; for example, grazing stimulated carbon storage in C_4 grasslands by 67% but decreased it in C_3 grasslands by 18% (McSherry and Ritchie 2013).

Species Shifts: Invasive Grasses and Woody Encroachment. The species composition, productivity, and carbon storage in grasslands are partly controlled by fire regimes, whether managed or unmanaged. Reduced fire frequency is associated with encroachment of woody plants into grassland ecosystems, while expansion of non-native, annual grasses such as cheatgrass can lead to increased fire frequency (see Figure 10.1, p. 402; Jones et al., 2015). Species shifts from perennial to annual vegetation may lead to reductions in productivity and carbon storage (Prater et al., 2006). For example, net carbon losses averaging 150 g per m^2 per year were observed for cheatgrass, mainly from increased decomposition rates (Verburg et al., 2004). Cheatgrass enhanced greenhouse gas (GHG) emissions, especially nitrous oxide (N_2O), and carbon cycling rates, compared with those for native perennial grasses (Norton et al., 2008). Further expansion of cheatgrass is expected to occur in response to rising temperatures across the western United States (Blumenthal et al., 2016).

Woody plant encroachment, with its increasing abundance of shrubs and trees, is one of the greatest threats to grasslands in North America, particularly with regard to changes in the magnitude and distribution of carbon stored in major terrestrial pools (Archer et al., 2001; Barger et al., 2011; Jackson et al., 2002; Knapp et al., 2008b). Changes in ecosystem carbon storage accompanying increases in

woody plants in grasslands represent a potentially significant but highly uncertain component of the carbon budget for North America (Houghton et al., 1999; Pacala et al., 2007), with positive, neutral, or negative effects documented (Barger et al., 2011). The most recent synthesis of studies quantifying the carbon consequences of woody plant encroachment in grasslands suggests that carbon in aboveground pools decreases in more water limited regions (i.e., mean annual precipitation < 330 mm) but increases in regions with greater precipitation (Barger et al., 2011; Knapp et al., 2008a). In the U.S. Great Plains, fire suppression with its associated woody encroachment from 1971 to 2005 is estimated to have increased total carbon stocks by an extra 5% relative to a nonfire-suppression scenario, with gains in woody biomes more than exceeding losses in grasslands (Bachelet et al., 2017). Changes in soil carbon from woody encroachment were not strongly related to aboveground carbon. However, loss of soil carbon is most likely to occur in humid grasslands, with increases in soil carbon apparent in arid regions (Barger et al., 2011; Jackson et al., 2002). Combining major aboveground and belowground pools, Barger et al. (2011) concluded woody plant encroachment generally would result in a net increase in ecosystem carbon stocks. Although some shrub-dominated ecosystems are more likely to lose carbon during drought periods than nearby grass-dominated systems (Scott et al., 2015), other areas indicate shrubs can maintain net carbon uptake despite drought (Petrie et al., 2015).

Woody plants are still increasing in many grasslands as a result of reduced fire frequency, rising CO_2, and increased precipitation intensity (Kulmatiski and Beard 2013). Because changes in carbon pools occur at very different rates above and below ground, ecosystem carbon changes driven by woody plant encroachment are likely to remain dynamic in the future. Overall, shifts in plant species composition and ecosystem structure represent a significant source of uncertainty in predicting future carbon cycling in grasslands.

10.3 Indicators, Trends, and Feedbacks

10.3.1 Future Projections of Carbon Stocks and Fluxes in Conterminous U.S. Grasslands

In estimating carbon stock and fluxes, several different models were used (see Key Finding 1, p. 400) to assess their projections, The LandCarbon project simulated future carbon stocks (see Figure 10.2, p. 404) and fluxes (see Figure 10.3, p. 406) using projections from MIROC A1B, A2, and B1 climate scenarios; FORE-SCE model; and EDCM (Liu et al., 2012b, 2014). Thus, these simulations combine the effects of land-use change and climate on carbon sequestration by grasslands in the conterminous United States (see Table 10.2, p. 403). While these model predictions are useful as general guidelines, additional empirical and simulation experiments are needed to disaggregate the effects of land-cover change from those of climate change and to examine regional differences in carbon cycling.

10.3.2 Impacts of Land-Use and Land-Cover Change on Future Carbon Cycling

Zhu et al. (2011) demonstrate that land-use and land-cover conversions were major drivers of the predicted changes in carbon storage in Great Plains grasslands. Future land-use change in the region (data provided by the *Intergovernmental Panel on Climate Change's Special Report on Emission Scenarios*; IPCC 2000) is driven by the demand for agricultural commodities, including biofuels, resulting in a 1.4% to 9.2% expansion of agricultural land by 2050, mostly at the expense of grasslands (–2.2% to –9.3%). Areas where woody vegetation expands into grassland because of fire suppression are re-classified as forest. This change tends to result in higher carbon stocks and uptake rates but also can be subject to catastrophic carbon losses in hot and dry fire years following wet years' boosting of fuel loads (Bachelet et al., 2017).

In the Great Plains, carbon stocks for the years 2001 to 2005 are assessed as 7,500 Tg C with 45.8% in agricultural lands, 34.9% in grasslands and

shrublands, 15.5% in the few existing forested areas, and almost 3% in wetlands. By 2050, models estimate those percentages will change to reflect a small increase in agricultural land carbon stocks (47%), a large decrease in grassland carbon stocks (29%), an increase in forestland carbon stocks (20.4%) due to woody encroachment and forest growth, and no change in carbon stocks of wetlands or other lands. Conversion of grasslands to agriculture may lead to a cumulative reduction in stored carbon of 26 to 157 Tg from 2001 to 2050, an amount which could contribute up to 4% loss of mean total carbon sequestration potential (Zhu et al., 2011). Shrub encroachment and afforestation cannot mitigate carbon losses to agricultural expansion. Fires are also a source of carbon loss. Areas burned and carbon emissions from fires vary both spatially and temporally due to climatic, biological, and physical factors. However, fires in grasslands were not projected to change significantly under future climate conditions when models did not include the role of annual invasives or fire suppression. Average fire emissions from grasslands range from 0.18 to 24.72 Tg CO_2 equivalent[1] (CO_2e) per year (Zhu et al., 2011).

10.3.3 Climate Change Impacts on Grassland Productivity

Numerous environmental factors interact to affect grassland production, including warming, rising CO_2, hydrology, and nutrient availability. Grassland productivity is very sensitive to variations in climate, especially precipitation and including both the mean and extremes such as droughts and floods (Huxman et al., 2004; Knapp et al., 2001, 2008b, 2015). Their sensitivity indicates a strong potential for climate change to alter carbon cycling in grasslands (see Key Finding 2, p. 400; Figure 10.5, p. 411). Productivity is predicted to decline in the southwestern United States and northern Mexico as a result of reduced precipitation and to increase in the northern Great Plains as a result of temperature and precipitation increases that allow an increase in growing season length (Hufkens et al., 2016; Polley et al., 2013; Reeves et al., 2014). However, significant projected increases in productivity did not arise until after 2030 because of scenarios projecting CO_2 fertilization and rising temperatures (Reeves et al., 2014).

North American grassland growth in this century was simulated based on hydrology and repeat-photography observations of vegetation greenness (Hufkens et al., 2016). Despite a projected increase in climate aridity by 2100, increases in fractional plant cover were predicted over almost 90% of the study area, with greater increases in cover and net carbon sequestration in the more northerly areas. The primary mechanism contributing to the projected increase in grassland growth was a shift to earlier leaf emergence in the spring and delayed leaf senescence in the autumn, both of which compensated for drought-induced reduction in plant productivity during the summer (Hufkens et al., 2016).

Predictions from the vegetation-hydrology model are supported by a climate manipulation experiment in Wyoming mixed-grass prairie, where the growing season started earlier in spring because of the warming treatment and ended later in autumn because of increased soil moisture made available by the elevated CO_2 treatment (Reyes-Fox et al., 2014). The lengthening of the growing season was dependent on a mix of C_3 and C_4 species adapted to different climate conditions. In the same experiment, greenness was enhanced (i.e., indicating increased aboveground biomass and cover) with warming and elevated CO_2, but the effects of seasonal and interannual rainfall variability were much stronger (Zelikova et al., 2015). High-precipitation years had two to three times greater vegetation greenness than dry years. Warming in combination with elevated CO_2 increased total plant biomass by an average of 25%, especially below ground (Mueller et al., 2016). Warming and elevated CO_2 also interacted to affect soil moisture and nitrogen availability (Mueller et al., 2016). While elevated CO_2 conditions increased soil moisture (Morgan et al., 2011), warming decreased soil moisture, and soil nitrate tended to follow trends opposite to those for elevated CO_2 (Mueller et al.,

[1] Carbon dioxide equivalent (CO_2e): Amount of CO_2 that would produce the same effect on the radiative balance of Earth's climate system as another greenhouse gas, such as methane (CH_4) or nitrous oxide (N_2O), on a 100-year timescale. For comparison to units of carbon, each kg CO_2e is equivalent to 0.273 kg C (0.273 = 1/3.67). See Box P.2, p. 12, in the Preface for details.

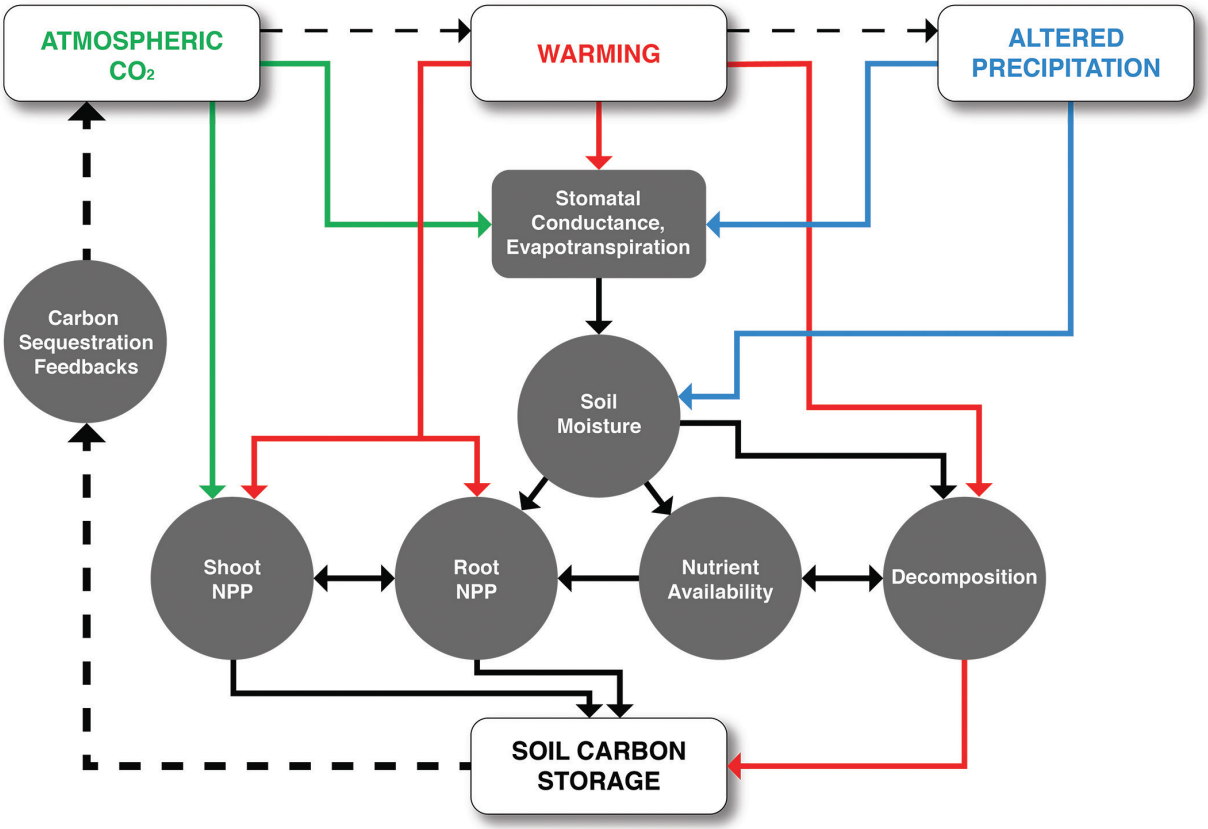

Figure 10.5. Interacting Effects of Rising Atmospheric Carbon Dioxide (CO_2), Warming, and Altered Precipitation on Grasslands. Climate variations can impact grassland plant productivity and soil organic matter (SOM) storage, which in turn are mediated by soil moisture and nutrient availability. Root and shoot net primary production (NPP) are correlated, and both are dependent on soil moisture and nutrient availability. Plant nutrient uptake can decrease soil nutrients, which may be made available during SOM decomposition. [Figure conception derived from numerous studies, including Hufkens et al., 2016; Morgan et al., 2011; Mueller et al., 2016; Reich and Hobbie 2013; Reyes-Fox et al., 2014; and Zelikova et al., 2015.]

2016). A warming experiment in desert grasslands suggested warming could reduce C_3 and C_4 grass carbon fixation rates and aboveground biomass, with no significant effects on shrub photosynthesis or growth (Wertin et al., 2015, 2017). Figure 10.5, this page, illustrates carbon cycle interactions and feedbacks associated with multiple climate change factors. Furthermore, changing seasonality of precipitation events, as well as more extreme weather conditions, are expected to affect carbon cycling increasingly more in the future (Knapp et al., 2008b).

Nutrient limitation may reduce the potential for CO_2 fertilization in grasslands, especially over decadal timescales (see Figure 10.5, this page). For example, a long-term experiment in a nutrient-poor grassland in Minnesota revealed that elevated CO_2 effects on NPP were dependent on soil nitrogen availability and experiment duration. During the first 3 years of the experiment, elevated CO_2 stimulated aboveground biomass by 11% and was not contingent on nitrogen availability, but over the longer term (4 to 13 years), the biomass response to elevated CO_2 increased by up to 20% with added nitrogen fertilizer (Reich and Hobbie 2013). However, in the coming decades, elevated temperature may enhance nitrogen availability, as shown by Mueller et al. (2016). Moreover, increasing nitrogen

deposition will stimulate NPP, up to a threshold, and GHG emissions also may follow a similar nonlinear response to nutrient loading (Gomez-Casanovas et al., 2016). Interacting effects of multiple global change factors still represent a large source of uncertainty in predicting carbon cycle responses (Norby and Luo 2004).

10.3.4. Trends and Climate Feedbacks from Soil Carbon Cycling

The effect of climate change on the stability of carbon in SOM pools is one of the largest sources of uncertainty in projections of climate-carbon interactions (Heimann and Reichstein 2008) because these pools are large and vulnerable to climate change (Davidson and Janssens 2006; see Key Finding 3, p. 400). In grasslands, decomposition of roots is thought to drive SOM accumulation (Jackson et al., 1996; Jobbagy and Jackson 2000), so processes affecting belowground productivity are likely to affect soil carbon storage (see Figure 10.5, p. 411). The importance of impacts from aboveground inputs compared to those from direct inputs via root production depends on climate, soil type, and plant species (Sanderman and Amundson 2008). Therefore, grassland species composition and productivity, both above and below ground, and their responses to climatic and land-use changes are key determinants of soil carbon storage. SOM decomposition rates vary with temperature and moisture and can be affected by plant-microbe interactions (van Groenigen et al., 2014) via nutrient uptake processes (Nie and Pendall 2016).

Soil Carbon Responses to Altered Precipitation. Precipitation is the most important climate driver of productivity in grasslands (Knapp and Smith 2001) and is likely to influence carbon storage in soils over longer timescales, via mechanisms related to both plant inputs and decomposition losses (see Figure 10.5, p. 411). A meta-analysis indicated that soil carbon content increased in response to both reductions and additions of moisture in grasslands (Zhou et al., 2016). Experimentally increased precipitation likely enhanced soil carbon pools via the stimulation of biomass inputs, whereas reduced precipitation may have enhanced the soil carbon pools by reducing SOM decomposition rates as well as by increasing allocation to root biomass production (Zhou et al., 2016).

Soil Carbon Responses to Warming. Earth System Models (ESMs) assume that warming will stimulate SOM decomposition at an exponential rate, leading to potentially strong positive feedbacks to climate change (Figure 10.5; Davidson and Janssens 2006). Experimental evidence of this assumption has been accumulating from numerous individual studies worldwide (Luo 2007). A recent synthesis of warming-experiment results confirms that SOM is vulnerable to warming and indicates that the magnitude of carbon loss depends on initial carbon stocks (Crowther et al., 2016). This study also showed that deserts and arid grasslands, with lower soil carbon pools, are less vulnerable to warming than colder ecosystems. A reduction in decomposition rates with warming-induced soil desiccation could potentially explain these results (Pendall et al., 2013).

Using results from field experiments to inform model parameters is a powerful way to reduce uncertainties, constrain the models, and enhance modeling tools to extrapolate results more broadly. Data from a 9-year warming experiment in tallgrass prairie were assimilated into a biogeochemistry model to demonstrate that soil carbon pools would decrease over the coming century (Shi et al., 2015). This study confirms that carbon in productive grasslands like the tallgrass prairie in Oklahoma can be vulnerable to warming, in part because of the resulting increased decomposition of a large, partially protected soil carbon pool. Key uncertainties were related to the mismatch between the long-term residence time of the large, recalcitrant soil carbon pool and the duration of the experiment (Shi et al., 2015).

Soil Carbon Responses to Rising CO_2 and Interactions with Multiple Drivers. While rising atmospheric CO_2 concentrations can stimulate grassland productivity above and below ground, especially in combination with warming (Mueller et al., 2016), increased productivity has not necessarily translated

into increased soil carbon storage (Luo et al., 2006). A meta-analysis revealed that carbon inputs to grasslands increased by 20% with experimentally increased CO_2, but this increase was accompanied by a 16.5% increase in the decomposition rate constant (van Groenigen et al., 2014). The "priming effect" that stimulates SOM decomposition may be caused by the increased microbial activity caused by increased belowground carbon inputs (Carney et al., 2007) and soil moisture (Pendall et al., 2003), and this effect may be "widespread and persistent" (van Groenigen et al., 2014). A simulation model calibrated to realistic field conditions in semiarid Wyoming grassland predicted that soil carbon would decrease with elevated CO_2 and increase with warming, because of indirect effects mediated by soil moisture (Parton et al., 2007). However, the importance of interactive effects of multiple climate changes in predictions of long-term soil carbon storage still needs to be confirmed with field results.

Few field experiments have been conducted that combine two or more climate drivers over a long enough duration to evaluate soil carbon responses (Luo et al., 2011), making realistic predictions of soil carbon sequestration challenging. A recent meta-analysis failed to uncover significant changes in soil carbon with the combined effects of elevated CO_2 and temperature, although belowground (i.e., root) production was significantly stimulated (Dieleman et al., 2012). While synthesis studies and meta-analyses are useful for discovering general patterns, they cannot distinguish mechanisms underlying these patterns. Major uncertainties in soil carbon storage and ecosystem carbon cycling remain because there are too few long-term, multifactor climate manipulation experiments to constrain mechanisms, feedbacks, and interactive effects among global change drivers.

10.4 Societal Drivers, Impacts, and Carbon Management

Because grassland vegetation is predominantly herbaceous (i.e., nonwoody), biomass carbon stocks in grassland systems are a small, transient carbon pool with soil constituting the dominant carbon stock. The main processes governing the carbon balance of grassland soils are the same as for other ecosystems—the photosynthetic uptake and assimilation of CO_2 into organic compounds and the release of gaseous carbon, primarily CO_2 but also methane (CH_4), through respiration and fire (see Key Finding 4, p. 400). In grasslands, carbon assimilation is directed toward production of forage by manipulating species composition and sometimes growing conditions (e.g., soil fertility and irrigation).

10.4.1 Grazing Management

For most grasslands in North America, grazing management is the primary feasible management practice that can be manipulated to alter soil carbon stocks. The capacity to increase grassland system carbon stocks is a function of 1) carbon stock changes that might be realized with a shift from suboptimal to best management practices and 2) the areal extent of grasslands that are not optimally managed (Conant and Paustian 2004). Estimates of the potential to sequester carbon in North American grasslands by improving grazing management practices seem likely to be on the order of tens of teragrams of carbon per year (Follett et al., 2001). Uncertainty across these and similar estimates stems from variation in soil carbon responses to management practices, which vary substantially from place to place. Some uncertainty also arises from limited information about past management and the extent to which those historical practices have depleted soil carbon stocks. Additionally, plot-level research indicates that a wide variety of practices could drive increases in soil carbon stocks (Chambers et al., 2016; Conant et al., 2001; Henderson et al., 2015). What is not clear is whether practices used in field experiments can be replicated reasonably under real-world conditions or the extent to which experiments are indicative of potentially observed real-world carbon stock rate changes (Conant et al., 2017).

Removal of some (30% to 50%) aboveground biomass through grazing can reduce the amount of carbon returned to the soil, potentially leading to reduced soil carbon stocks (Conant et al., 2017).

Similarly, shifts in species composition in response to grazing could lead to reductions in carbon inputs and soil carbon stocks. Some of the carbon lost from grassland soils can be recovered with changes in management practices that increase carbon inputs, stabilize carbon within the system, or reduce carbon losses (Conant et al., 2017; Eagle and Olander 2012). Adaptive and intensive grazing practices can increase soil carbon stocks (Machmuller et al., 2015; Teague et al., 2011). However, the management practices that promote soil carbon sequestration would need to be maintained over decades to avoid subsequent losses of sequestered carbon.

10.4.2 Fire Suppression and Woody Encroachment

Grazing management, fire suppression, and climate interactively control grassland species composition and productivity, and these responses vary regionally. Woody plant cover is increasing in many grasslands because of management activities such as fire suppression and anthropogenic GHG emissions that increase atmospheric CO_2 concentrations (Kulmatiski and Beard 2013). The most recent syntheses suggest that carbon in aboveground pools decreases in regions with more-limited water (mean annual precipitation < 330 mm) but increases in regions with greater precipitation (Barger et al., 2011; Knapp et al., 2008b). For example, fire suppression in Kansas allowed the expansion of *Juniperus virginia* that was associated with rapid increases in carbon stocks in vegetation and soils (McKinley and Blair 2008). In the more arid Chihuahuan Desert, shrub encroachment related to historical over-grazing led to higher net carbon uptake rates (Petrie et al., 2015) but may lead to additional loss of grass vegetation (Thomey et al., 2014). Soil carbon pools may increase with woody encroachment, depending on other disturbance factors, especially fire (Barger et al., 2011). If management policies continue to allow woody plants to expand into native grasslands, the central United States may become a significant regional carbon sink (McKinley and Blair 2008), given sufficient precipitation.

Regional responses to management and climate change are partly related to distinct evolutionary pressures. The combination of grazing and aridity in the Great Plains grasslands may have favored traits that impart resistance to both those disturbances (Milchunas et al., 1988; Moran et al., 2014; Quiroga et al., 2010). In contrast, desert grasslands evolved the ability to rapidly respond to and effectively use highly variable precipitation (McClaran 1997), though often requiring years to recover from disturbance (Peters et al. 2012) and thus allowing rapid expansion of woody species (McClaran et al., 2010). If the frequency of burning increases in mesic tallgrass prairie, decreased nitrogen may become a limiting factor, eventually diminishing aboveground production (Soong and Cotrufo 2015). Thus, fire regime management can influence carbon storage via its effects on above- and belowground production, as well as inputs of recalcitrant, pyrogenic organic matter to soil.

10.4.3 Land Conversion

Agricultural policies can have a large influence on land-use change. For example, in the U.S. Great Plains during 1973 to 2000, grassland and shrubland area expanded by 2.2% while agricultural area decreased by 1.8%, in part related to farm policy programs such as the Conservation Reserve Program (CRP; landcovertrends.usgs.gov/gp/eco43Report.html). However, the area held in CRP peaked in 2007 at 37 million acres and has since declined (Ahlering et al., 2016). In the coming three decades, agricultural expansion is expected to continue to reduce the extent of grasslands by 2% to 9% by 2050 (see Section 10.3.2, p. 409; Zhu et al., 2011), depending on annual crop prices (Stubbs 2014).

Grasslands generally take up and store more carbon than croplands; for example, in the Great Plains, the average uptake rates were about 45 g C per m^2 per year for grasslands and 31 g C per m^2 per year for croplands from 2000 to 2008 (Wylie et al., 2016). Soil carbon losses occur when native grasslands are initially tilled, with the amount determined by the tillage method and the soil's initial carbon content. In a modeling study, this "carbon debt" was repaid

after 2 to 25 years of no-till corn ethanol production, but that process was 50% longer in a full-tillage production scenario (Kim et al., 2009). Moreover, GHG emissions from croplands tend to be higher than those from grasslands, especially when CH_4 and N_2O are considered. Protection of grasslands from conversion to croplands in the northern mixed-grass prairie pothole region of the Dakotas would reduce emissions significantly, but carbon offsets alone cannot compete with high market prices for corn (Ahlering et al., 2016). For more details on the effects of agricultural management on carbon cycling, see Ch. 5: Agriculture, p. 229.

10.5 Synthesis, Knowledge Gaps, and Outlook

10.5.1 Synthesis

Grasslands are globally important carbon sinks that are resilient to climate change and managed grazing because the mixture of native species that occur are adapted to variable climatic conditions and grazing pressure. In drier regions, such as the southwestern United States and Mexico, grasslands may lose carbon in response to droughts or overgrazing. Mesic grasslands in Florida have stored vast amounts of soil carbon, which may be vulnerable to losses from fire and flooding, and CH_4 emissions from these and other poorly drained grasslands can be significant. Changes in the geographic extent of grasslands caused by land-use change, including cropping and grazing management, will affect grassland carbon cycling. The net uptake rate of carbon is higher in grasslands than in agricultural lands, but management that takes carbon storage into consideration may mitigate potential carbon losses. Invasive species also are likely to alter grassland carbon cycling: woody species such as juniper or mesquite may increase net carbon uptake while herbaceous invasive species, such as cheatgrass, may diminish net carbon uptake.

10.5.2 Knowledge Gaps

Grassland productivity and carbon cycling are linked very closely to variations in precipitation and soil moisture availability in space and time. Changes in climate that lead to altered moisture availability are likely to affect the ability of grasslands to store carbon. Therefore, one of the main sources of uncertainty in predicting grassland carbon cycling is related to predictions of future precipitation, in terms of means, extremes, and seasonal distribution. The forecasted intensification of the global hydrological cycle will manifest in many ways, including increased interannual precipitation variability, more frequent extreme precipitation years (wet and dry), and alterations in annual precipitation amount (IPCC 2013). Recent climatological trends have supported these predictions (Fischer and Knutti 2014; Min et al., 2011). In grasslands, carbon uptake processes have been shown to be quite responsive to precipitation amount and event size and timing (Cherwin and Knapp 2012; Goldstein and Suding 2014; Heisler-White et al., 2008, 2009; Knapp et al., 2008b; Kulmatiski and Beard 2013; Thomey et al., 2011), but both positive and negative effects have been documented. Resolving the effects on carbon cycling from altered precipitation regimes—including seasonality—in future grasslands will reduce uncertainty in responses (Knapp et al., 2008b). Moreover, also unknown are future effects on carbon cycling from interactions between climate change and species composition. Additional simulations with dynamic vegetation models, including management parameters such as fire suppression, will help reduce these uncertainties (Bachelet et al., 2017).

Model intercomparison projects that address large differences in future projections of carbon cycling in grasslands and other ecosystem types also will reduce uncertainties (Medlyn et al., 2015). Methodological differences in estimating regional- to continental-scale carbon stocks and fluxes have resulted in large apparent uncertainties in budgets. For inventory methods, these uncertainties appear to stem from extrapolating carbon stocks and fluxes from point measurements to regional scales based on land-use classifications. For land-surface models, uncertainties can result from different assumptions, drivers, and processes. For atmospheric inverse models, the attribution of specified land areas may not align well with other approaches. For all these

methods, inconsistencies in the depth of soil carbon can lead to large differences in stocks and process rates. Reconciling these divergent results likely will lead to improved understanding of processes and narrow the range of uncertainty in carbon forecasts.

Projections of soil carbon trends in response to future climate and land-use changes remain highly uncertain, particularly in warm, dry areas of Mexico and the U.S. Southwest and at high northern latitudes where data to inform modeling are limited. One uncertainty is related to the depth of soil carbon storage, with most models considering only the top 20 cm. However, validation and calibration datasets are not readily available, so models are rarely updated (e.g., Liu et al., 2003), and there is disagreement about which drivers of soil carbon dynamics should be included in models (Wieder et al., 2015). A recent study that simulated results from several multifactor climate change experiments indicated that productivity and decomposition responded more to increased precipitation and elevated CO_2 in drier sites, including grasslands, than they did in wetter sites (Luo et al., 2008). The four tested ecosystem models all demonstrated significant interactive effects of warming, elevated CO_2, and altered precipitation, although results for different sites varied because model formulations differed (Luo et al., 2008). These disparate findings demonstrate that rigorously evaluating model assumptions against experimental results will improve ESM projections (Medlyn et al., 2015).

10.5.3 Outlook

Grasslands, the most extensive land-use type in the continental United States when combined with rangelands, shrublands, and pastures (Reeves and Mitchell 2012), are expected to maintain net carbon uptake at least until the middle of this century. The most significant threats to this carbon uptake potential likely will be related to land management and land use, along with changes in the precipitation regime associated with ongoing climate change.

SUPPORTING EVIDENCE

KEY FINDING 1

Total grassland carbon stocks in the conterminous United States, estimated to be about 7.4 petagrams of carbon (Pg C) in 2005, are projected to increase to about 8.2 Pg C by 2050. Although U.S. grasslands are expected to remain carbon sinks over this period, the uptake rate is projected to decline by about half. In the U.S. Great Plains, land-use and land-cover changes are expected to cause much of the change in carbon cycling as grasslands are converted to agricultural lands or to woody biomes (*medium confidence*).

Description of evidence base

Total carbon stocks are from Table 10.2, p. 403, based on LandCarbon project estimates (landcarbon.org/categories). Various efforts confirm that the U.S. and North American grasslands in recent years have been a weak carbon sink (i.e., mostly within the range of 10 to 40 g per m^2 per year; Hayes et al., 2012; Liu et al., 2012b; Raczka et al., 2013; Wylie et al., 2016; Xiao et al., 2014; Zhang et al., 2011). Recent results generated from the assessment of carbon sequestration potentials in the United States conducted by the U.S. Geological Survey (Zhu and Reed 2012, 2014; Zhu et al., 2011) provided more integrated grassland carbon assessment. Land-use change scenarios and spatial dynamics were developed empirically by ecoregions across the United States under the Intergovernmental Panel on Climate Change (IPCC) scenarios A1B, A2, and B1 (Sleeter et al., 2012; Sohl et al., 2007), which are considered to be similar to representative concentration pathway (RCP) scenarios (Knutti and Sedláček 2013). Carbon dynamics in grassland ecosystems were simulated with the General Ensemble Biogeochemical Modeling System (GEMS) using three climate projections: the Second Generation Coupled Global Climate Model (CGCM2), Australia's national Commonwealth Science and Industry Research Organization (CSIRO), and Model for Interdisciplinary Research on Climate (MIROC) for each of the three IPCC scenarios (Liu et al., 2012b, 2014). The data included in this report include simulations from two process-based models: CENTURY (Parton et al., 1987) and the Erosion-Deposition–Carbon-Model (EDCM; Liu et al., 2003), and both were encapsulated in GEMS. The findings are supported by a recent synthesis of eddy covariance data with remote sensing, which shows that grasslands take up somewhat more carbon than crops in the Great Plains, although both were weak carbon sinks from 2000 to 2008 (Wylie et al., 2016).

Major uncertainties

There are significant differences in evaluation of grassland carbon stocks and fluxes (Hayes et al., 2012; Raczka et al., 2013; Zhu and Reed 2014). The primary source of model difference comprises modeling method (i.e., inventory, flux towers, inversion, and process-based modeling) and land-cover characterization and spatial resolution. For example, the LandCarbon study (Zhu and Reed 2012, 2014; Zhu et al., 2011) combined grass and shrub into grassland and considered fire disturbance, while Zhang et al. (2011) used data from 15 flux towers at natural grassland and pastures or hay sites but without considering fires.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

The magnitudes of the estimates of carbon stocks and fluxes vary depending on the method used, indicating a medium to low level of confidence in the results.

Summary sentence or paragraph that integrates the above information

Grasslands appear very likely to be weak carbon sinks and will remain so for at least the coming three decades, but reconciling different methods will reduce uncertainties in the quantities.

KEY FINDING 2

Increasing temperatures and rising atmospheric carbon dioxide (CO_2) concentrations interact to increase productivity in northern North American grasslands, but this productivity response will be mediated by variable precipitation, soil moisture, and nutrient availability (*high confidence, very likely*).

Description of evidence base

Experimental manipulations in the field provide evidence of climate change effects on grassland productivity by up to 33%, but this is contingent on nutrient and moisture availability (e.g., Morgan et al., 2011; Mueller et al., 2016; Reich and Hobbie 2013). Spatially distributed observations of vegetation phenology (i.e., greenness) and carbon fluxes combined with empirical modeling provide evidence of regional differences in grassland responses to future climate change (Hufkens et al., 2016). Simulation models are in general agreement with empirical evidence that carbon stocks will increase in grasslands in the coming three to four decades (Zhu et al., 2011). In grasslands, carbon uptake is responsive to precipitation amount and event size and timing, with both positive and negative effects documented, but droughts are associated with carbon losses across all grasslands (Cherwin and Knapp 2012; Goldstein and Suding 2014; Heisler-White et al., 2008, 2009; Knapp et al., 2008b; Kulmatiski and Beard 2013; Thomey et al., 2011).

Major uncertainties

The largest source of uncertainty is related to future precipitation regimes in the grassland biomes of North America, with both increases and decreases in precipitation predicted (IPCC 2013). The degree to which altered precipitation regimes will affect carbon cycling in future grasslands is uncertain (Knapp et al., 2008b). The relative response of grassland productivity to moisture availability is contingent upon prior conditions, which vary temporally and spatially (Heisler-White et al., 2009). Empirical models represent grassland phenology and productivity well, but they lack explicit physiological processes, leading to uncertainties in mechanisms underlying ecosystem responses to climate change (Hufkens et al., 2016).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Confidence is high that grassland production will increase with precipitation as atmospheric CO_2 and temperature increase in the coming three to four decades, based on empirical evidence from field experiments.

Estimated likelihood of impact or consequence, including short description of basis of estimate

If grassland productivity decreases in response to climate change, such as reduced precipitation, forage production for livestock is very likely to be at risk. This has been demonstrated by numerous experiments and models as explained above in the description of evidence base.

Summary sentence or paragraph that integrates the above information

Grassland productivity is highly likely to respond positively to increased precipitation and temperature, especially in the Northern Great Plains. Neutral or negative responses of productivity to warming in the Southern Great Plains, the southwestern United States, and Mexico may be offset by positive responses to elevated CO_2.

KEY FINDING 3

Soil carbon in grasslands is likely to be moderately responsive to changes in climate over the next several decades. Field experiments in grasslands suggest that altered precipitation can increase soil carbon, while warming and elevated CO_2 may have only minimal effects despite altered productivity (*medium confidence, likely*).

Description of evidence base

Meta-analysis of numerous field experiments showed that soil carbon stocks increase when precipitation is increased or decreased in grasslands (Zhou et al., 2016). Meta-analysis also showed that elevated CO_2 increased soil carbon decomposition rate, limiting carbon storage potential (van Groenigen et al., 2014). Field experiments indicate that soil carbon stocks decrease with warming, especially in regions where stocks are high to begin with (Crowther et al., 2016), although warming-induced soil carbon losses from grasslands may be insignificant (Lu et al., 2013). These results are confirmed in some simulation experiments (e.g., Parton et al., 2007; Shi et al., 2015).

Major uncertainties

Major uncertainties in soil carbon storage come from insufficient understanding of physical and biological mechanisms that determine the stability of soil carbon. Physical mechanisms underlying carbon stability in soil, such as protection within aggregates and their sensitivity to climate change, are still poorly described (Heimann and Reichstein 2008). In particular, regulation of soil organic matter decomposition by microbe-plant interactions is poorly understood and not well represented in models (Wieder et al., 2015). Improving mechanistic understanding of soil carbon dynamics, and incorporating key mechanisms into models, will reduce uncertainties in future carbon cycle predictions (Todd-Brown et al., 2013).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Mechanistic understanding of soil carbon stability in the face of climate change is still limited, leading to only medium confidence levels regarding the response of soil carbon to climate changes.

Estimated likelihood of impact or consequence, including short description of basis of estimate

Soils in grasslands are not likely to respond strongly to climate change; small carbon losses or gains could occur in the future with warming or elevated CO_2. Larger carbon gains are likely to occur with increased precipitation.

Summary sentence or paragraph that integrates the above information

Mechanisms regulating soil carbon storage in response to climate change can be incorporated into models to improve confidence in model predictions of future carbon cycling.

KEY FINDING 4

Carbon stocks and net carbon uptake in grasslands can be maintained with appropriate land management including moderate levels of grazing. Fire suppression can lead to encroachment of woody vegetation and increasing carbon storage in mesic regions, at the expense of grassland vegetation (*high confidence, likely*).

Description of evidence base

Studies of carbon fluxes using eddy covariance indicate that moderate grazing allows grasslands to continue to be net carbon sinks, but heavy grazing diminishes their capacity to take up carbon (Frank 2004; Morgan et al., 2016; Polley et al., 2008; Risch and Frank 2006). Soil inventory studies indicate that moderate to light grazing does not negatively affect carbon stocks (Conant et al., 2001, 2017), and improving grazing management can augment carbon stocks (Chambers et al., 2016). Carbon cycle responses to woody encroachment are determined from inventories of carbon stocks in vegetation and soils in plots that have been experiencing woody encroachment for different periods of time (Barger et al., 2011; Knapp et al., 2008a).

Major uncertainties

Uncertainties in grazing management impacts on carbon cycling in grasslands stem mainly from the regional variations in soil carbon responses to management, from challenges in designing scientific studies that adequately represent real-world management practices, and from limitations faced when extrapolating plot-level studies to broader areas (Conant et al., 2017). Interactive effects of grazing, climate, soil type and plant community composition on carbon storage are not well constrained (McSherry and Ritchie 2013). The magnitude of carbon accumulation below ground in response to woody encroachment is poorly constrained, but change in carbon pools above ground is well known (Barger et al., 2011; Knapp et al., 2008a). Fire regimes are changing with increasing temperatures and altered vegetation; uncertainties in future fire risk add uncertainty to projections of carbon budgets.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is high confidence with general agreement across several studies that moderate to light grazing will not have a negative impact on carbon cycling.

Estimated likelihood of impact or consequence, including short description of basis of estimate

Woody encroachment likely will lead to increased carbon storage in mesic grasslands.

Summary sentence or paragraph that integrates the above information

Carbon likely will continue to accumulate for the next several decades in grasslands if they are appropriately managed.

SUPPORTING EVIDENCE FOR TABLES

Table 10.1, p. 401, is based on Hayes et al. (2012). The areas for grasslands by countries and the continent are from the models and inventory analyses used in their study (see Table S10 in Hayes et al., 2012). The area for "Others" is smaller for the models than the inventory analysis mainly because the latter includes urban areas. Inventory estimates are the sum of livestock methane

(CH_4) emissions + livestock carbon dioxide (CO_2) emissions + grassland net ecosystem exchange (NEE) for Canada and the United States. Taiga was excluded from Canada grassland NEE and livestock emissions. For Mexico, the number for "Others" was used because extracting grassland NEE was not possible. Atmospheric inversion models (AIMs) and land-surface models (LSMs) are from Table 2 in Hayes et al. (2012) and do not include CH_4 emissions or human settlement emissions. Thus, the AIM values of NEE for "Others" should be representative of grassland and pastureland NEE. Area estimate for grasslands: www.statista.com/statistics/201761/projection-for-total-us-grassland-area-from-2010.

Table 10.2, p. 403. Carbon fluxes and stocks for grasslands and shrublands in the conterminous United States summarized from the LandCarbon project (landcarbon.org/categories). Values are averages of the A1B, A2, and B1 climate scenarios and estimated using the FOREcasting SCEnarios of land-use change (FORE-SCE) model and the Erosion-Deposition-Carbon-Model (EDCM), CENTURY, and PBN carbon models (Liu et al., 2012b, 2014; Zhu et al., 2011). Climate projections based on emissions scenarios used by the LandCarbon Project are considered to be similar to representative concentration pathway (RCP) scenarios (Knutti and Sedláček 2013). Negative fluxes indicate carbon losses from the ecosystem; positive fluxes indicate carbon gains by the ecosystem. The total flux is considered to be the net ecosystem carbon balance (NECB). Land-cover classification could be a source of differences. Flux towers mostly measure actual grassland and rangeland, whereas the General Ensemble Biogeochemical Modeling System (GEMS) includes both grassland and shrubland. The conterminous United States has about 1 million km^2 of grassland and 1.3 million km^2 of shrubland (from Liu et al. land-cover data). The area difference is notable. Land conversion to and from agriculture and permanent grassland loss to urban land all contribute to the total carbon number.

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11 Arctic and Boreal Carbon

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KEY FINDINGS

1. Factors that control terrestrial carbon storage are changing. Surface air temperature change is amplified in high-latitude regions, as seen in the Arctic where temperature rise is about 2.5 times faster than that for the whole Earth. Permafrost temperatures have been increasing over the last 40 years. Disturbance by fire (particularly fire frequency and extreme fire years) is higher now than in the middle of the last century (*very high confidence*).

2. Soils in the northern circumpolar permafrost zone store 1,460 to 1,600 petagrams of organic carbon (Pg C), almost twice the amount contained in the atmosphere and about an order of magnitude more carbon than contained in plant biomass (55 Pg C), woody debris (16 Pg C), and litter (29 Pg C) in the boreal and tundra biomes combined. This large permafrost zone soil carbon pool has accumulated over hundreds to thousands of years. There are additional reservoirs in subsea permafrost and regions of deep sediments that are not added to this estimate because of data scarcity (*very high confidence*).

3. Following the current trajectory of global and Arctic warming, 5% to 15% of the soil organic carbon stored in the northern circumpolar permafrost zone (mean 10% value equal to 146 to 160 Pg C) is considered vulnerable to release to the atmosphere by the year 2100. The potential carbon loss is likely to be up to an order of magnitude larger than the potential increase in carbon stored in plant biomass regionally under the same changing conditions (*high confidence, very likely*).

4. Some Earth System Models project that high-latitude carbon releases will be offset largely by increased plant uptake. However, these findings are not always supported by empirical measurements or other assessments, suggesting that structural features of many models are still limited in representing Arctic and boreal zone processes (*very high confidence, very likely*).

Note: Confidence levels are provided as appropriate for quantitative, but not qualitative, Key Findings and statements.

11.1 Introduction

11.1.1 Drivers of Carbon Cycle Change

This assessment focuses on Arctic and boreal carbon pools and fluxes, particularly those included within the northern circumpolar permafrost (perennially frozen ground) zone, which includes tundra and a large fraction of the boreal biome. Current knowledge of the state of organic carbon in soils and vegetation is evaluated herein, along with the potential for these pools to change over time in response to disturbance regimes and changing climate. Changes in temperature and precipitation act as gradual "press" (i.e., continuous) disturbances that directly affect carbon stocks and fluxes by modifying the biological processes of photosynthesis and respiration (LTER 2007). Climate changes also can modify the occurrence and magnitude of biological disturbances such as insect outbreaks as well as abrupt physical disturbances such as fire, extreme drought, and soil subsidence and erosion resulting from ice-rich permafrost thaw. These "pulse" (i.e., discrete) disturbances often are part of the ongoing successional cycle in Arctic and boreal ecosystems, but changing rates of occurrence alter the landscape distribution of successional ecosystem states, in turn, affecting landscape carbon storage. This overview introduces recent and expected trends in these drivers; their combined impact on carbon pools and fluxes is detailed later in the chapter.

Continuous Press Disturbances: Temperature, Precipitation

The most pronounced change in high-latitude climate during the last 40 to 50 years is the increase in mean annual surface air temperatures (see Figure 11.1, p. 430). Global temperature change is amplified in high-latitude regions, as seen in the Arctic where temperature rise is about 2.5 times faster than that

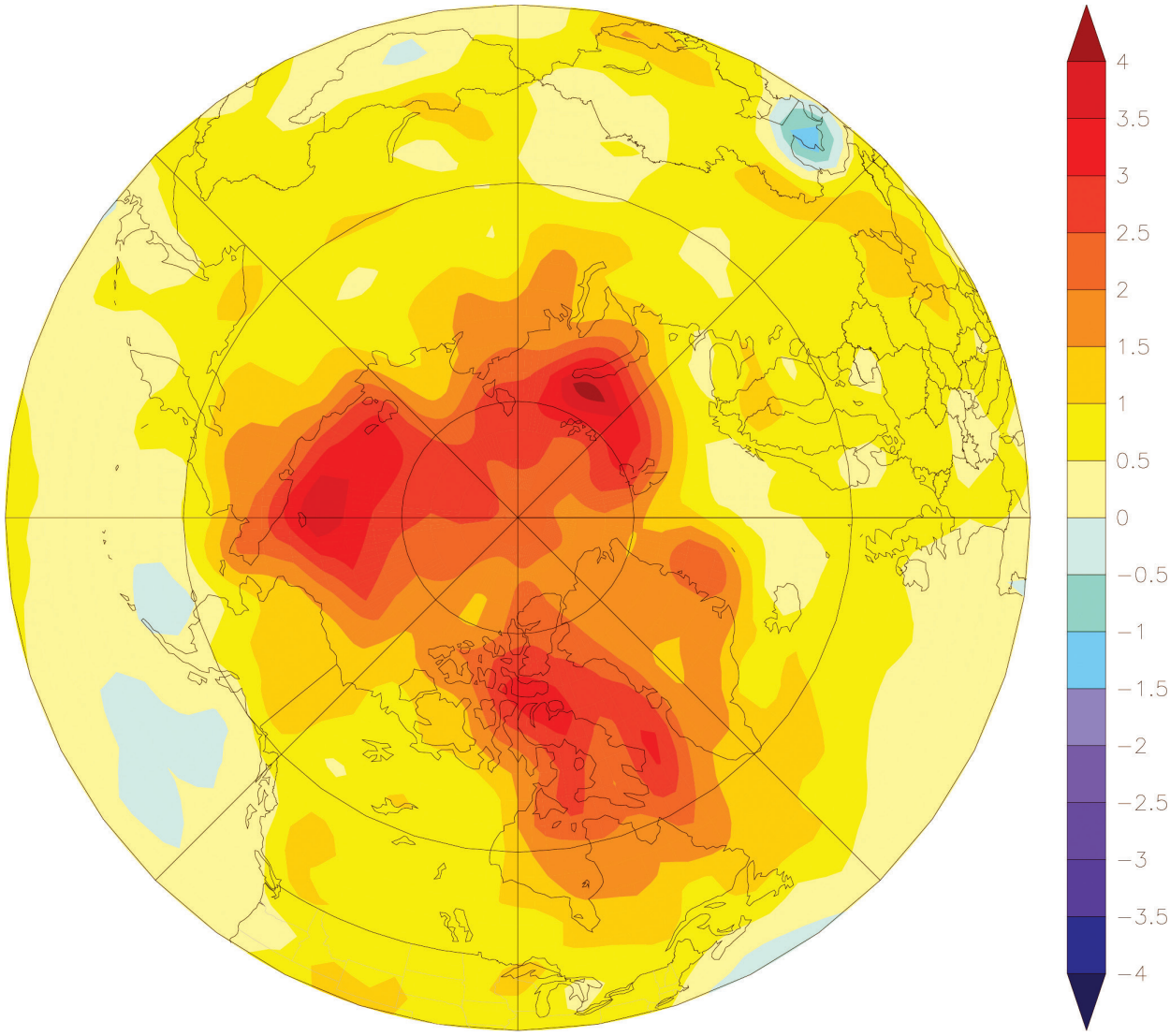

Figure 11.1. Difference in Mean Annual Arctic Surface Air Temperatures (in ºC) Between the Period 2001 to 2015 and the Baseline Period 1971 to 2000. Data are from the Goddard Institute for Space Studies Surface Temperature Analysis (GISTEMP) within the National Aeronautics and Space Administration (data.giss.nasa.gov/gistemp). [Figure source: Reprinted from Overland et al., 2014, used with permission under a Creative Commons license (CC-BY-NC-ND 3.0).]

for the whole Earth (IPCC 2013). Air temperature increased in the Arctic by 1 to 2°C over the last 20 to 30 years (Overland et al., 2014). This increase was even more substantial (>3°C) in some regions of the Arctic Ocean and over the central and eastern parts of the Canadian Arctic Archipelago. Warming is most noticeable during the winter, but summer temperatures also are on the rise, and this differential is expected to continue in the future. The average air temperatures in the cold season (November through April) in Alaska, northern Canada, and in a large portion of Siberia have increased by 2 to 4°C between 1961 and 2014. In contrast, the temperature increase in the warm half of the year (May through October)

was between 1 and 2°C for the same regions and time interval (data.giss.nasa.gov/gistemp/maps).

The degree of projected future warming—dependent on the scenario of changes in greenhouse gas (GHG) emissions through time—ranges widely for different Earth System Models (ESMs). By 2050, the differences in these projections as a result of various Representative Concentration Pathway (RCP) forcing scenarios (e.g., RCP4.5 and RCP8.5) are not large. Averaged across 36 ESMs, the projected mean annual air temperature increases for 60°N to 90°N by 2050 is about 3.7°C compared to the 1981 to 2005 period 2°C increase in the summer and 5.3°C increase in the winter (Overland et al., 2014). However, projections for 2100 differ significantly for RCP4.5 and RCP8.5. For 2100, the same models project a 4.3°C increase in mean annual temperature for RCP4.5 and an 8.7°C increase for RCP8.5. The summers are predicted to be warmer by 2.3°C for RCP4.5 and by 5.1°C for RCP8.5; winter temperatures are projected to rise by 6 and 12.5°C, respectively. Projected changes in precipitation are less consistent and vary significantly from region to region and over different time intervals. However, most models project increasing precipitation in the Arctic, especially in the winter. The percentage increases are largest in the cold season and, as a result of the RCP8.5 scenario, over the Arctic Ocean (IPCC 2013).

Permafrost is technically defined as subsurface Earth materials (e.g., rock, soil, and ice) remaining <0°C for at least 2 consecutive years. Observed changes in climate triggered a substantial increase in permafrost temperatures during the last 40 years (Romanovsky et al., 2010, 2016; Smith et al., 2010). Based on data from a selection of sites with both long-term records and good geographical coverage, annual mean permafrost temperatures generally have been increasing (Noetzli et al., 2016; Romanovsky et al., 2016; see Figure 11.2, p. 432). The greatest temperature increase is found in colder permafrost (approximately –15 to –2°C) in the Arctic where current permafrost temperatures are more than 2 to 2.5°C higher than they were 30 years ago. In areas with warmer permafrost (approximately –2 to 0°C)—such as the southern and central Mackenzie Valley, interior Alaska, Siberia's discontinuous permafrost zone, and the Nordic region—the absolute temperature change in permafrost has been much smaller, with increases generally less than 1°C since the 1980s.

Permafrost change in these warmer regions typically involves near-surface degradation, as measured by the thickness of the seasonally thawed layer at the soil surface, which thaws in summer and refreezes in winter. This parameter is defined as the active layer thickness (ALT), the maximum thaw depth at the end of the summer. ALT responds more to short-term variation in climate as compared to the deeper ground temperature. Ground-based records of ALT, therefore, exhibit greater interannual variability, primarily in response to variation in summer temperature (Smith et al., 2009). Although decadal trends in ALT vary by region (Shiklomanov et al., 2012), most regions where long-term ground-based ALT observations are available show an increase in ALT during the last 5 to 10 years (Romanovsky et al., 2016). These measured ALT increases actually may underestimate surface permafrost degradation because the ground surface can settle with permafrost thaw, obscuring actual changes in the permafrost surface using this metric (Shiklomanov et al., 2013). Recently, several direct and indirect remote-sensing methods were proposed for regional ALT estimations over large geographical areas using both airborne and spaceborne sensors (Gogineni et al., 2014; Liu et al., 2012; Pastick et al., 2013). However, these methods are still in development and thus are not yet used in an operational mode. The increase in ground surface temperatures over the last 30 years triggered long-term permafrost thaw in natural conditions at many locations not only within the discontinuous permafrost zone, but also in the cold continuous permafrost (Drozdov et al., 2012; James et al., 2013; Liljedahl et al., 2016; Malkova et al., 2014; Melnikov et al., 2015).

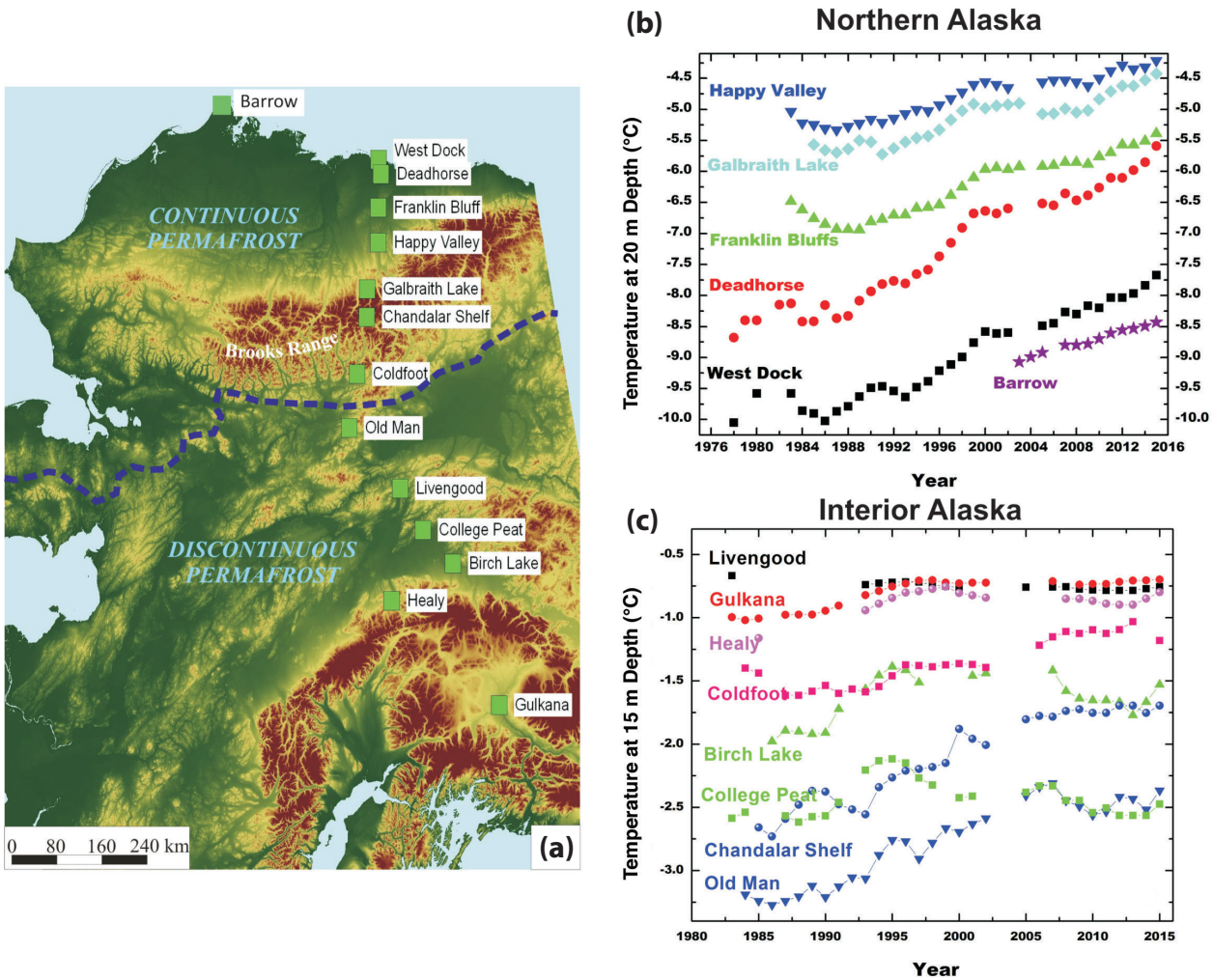

Figure 11.2. Deep Permafrost Temperature Across a Latitudinal Transect in Alaska. (a) Location of the measurement stations. Changes for northern Alaska **(b)** and interior Alaska **(c)**. Rising permafrost temperatures are greatest for cold permafrost. [Figure source: Adapted and updated with new time-series data from the National Oceanic and Atmospheric Administration's 2012 Arctic Report Card (NOAA 2012).]

Episodic Pulse Disturbances: Wildfire, Abrupt Thaw

Beyond documented change in climate that has affected permafrost directly as a press disturbance, recent observations suggest that climate-sensitive pulse disturbance events, such as wildfire and abrupt permafrost thaw, are increasing in frequency, intensity, and extent across many high-latitude regions. Shifts in pulse disturbances are propelled by gradual climate warming (Jorgenson 2013); extreme weather events (Balser et al., 2014); insect and disease outbreaks (Kurz et al., 2008); and interactions among disturbances, such as those between abrupt thaw and wildfire (Hu et al., 2010; Jones et al., 2015; Lara et al., 2016) or human activities (Jorgenson et al., 2006).

Of all pulse disturbance types, wildfire affects the most land area annually and is currently the best characterized at the regional to continental scale. Fire activity is intimately coupled to climatic variation in regions where fuel buildup is not limiting to burning (van Leeuwen et al., 2014). Recent climate

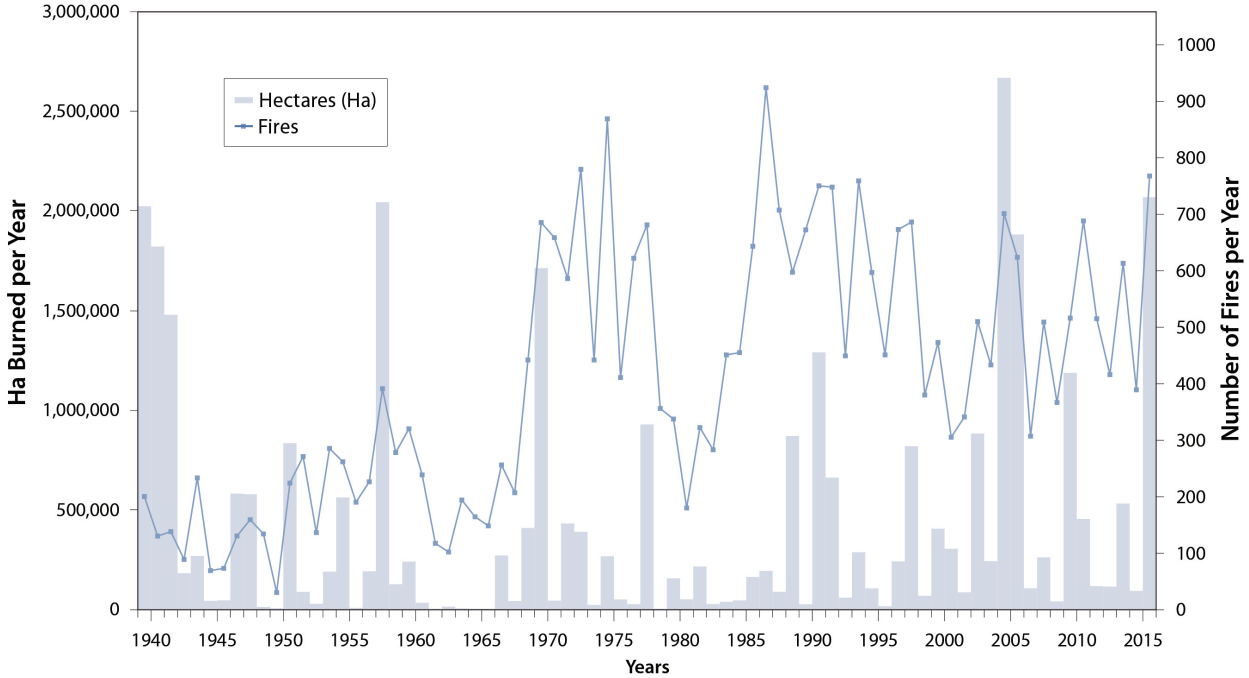

Figure 11.3. Wildfire Occurrence in Alaska from 1939 to 2015. Bars on the left y-axis show area burned in hectares per year. Right y-axis and points connected by a line show the number of fires per year. [Figure source: Redrawn from Alaska Interagency Coordination Center, used with permission.]

warming has been linked to increased wildfire activity in the boreal forest regions of Alaska (see Figure 11.3, this page; Kelly et al., 2013) and western Canada (Flannigan et al., 2009; Kasischke and Turetsky 2006), where fire has been part of historic disturbance regimes (Johnson 1992). Based on satellite imagery, an estimated 8 million hectares (ha) of boreal area was burned globally per year from 1997 to 2011 (Giglio et al., 2013; van der Werf et al., 2010). Roughly 50% of this burned area is forested; the rest is classified as low-density forest savanna, shrubland, or, in the case of boreal Eurasia, cropland. Eurasian boreal forests account for 69% of global boreal forest area and approximately 70% of the boreal area burned (Giglio et al., 2013). However, extreme fire years in northern Canada during 2014 and Alaska during 2015 doubled the long-term (1997 to 2011) average area burned annually in this region, surpassing Eurasia to contribute 60% of the global boreal area burned (Giglio et al., 2013; Mu et al., 2011; Randerson et al., 2012; van der Werf et al., 2010). These extreme North American fire years were balanced by lower-than-average area burned in Eurasian forests, resulting in a 5% overall increase in global boreal area burned. Decadal trends (Flannigan et al., 2009; Kasischke and Turetsky 2006) and paleoecological reconstructions (Kelly et al., 2013) support the idea that area burned, fire frequency, and extreme fire years are higher now than in the first half of the last century, or even the last 10,000 years.

Fire also appears to be expanding as a novel disturbance into tundra and forest-tundra boundary regions previously protected by cool, moist climate (Hu et al., 2010, 2015; Jones et al., 2009). The annual area burned in Arctic tundra is generally small compared to that in the forested boreal biome. However, the expansion of fire into tundra that has not experienced large-scale disturbance for centuries causes large reductions in soil carbon stocks (Mack et al., 2011), shifts in vegetation composition and

productivity (Bret-Harte et al., 2013), and can lead to widespread permafrost degradation (Jones et al., 2015). In Alaska—the only region where estimates of burned area exist for both boreal forest and tundra vegetation types—tundra burning averaged approximately 0.3 million ha per year during the last half century (French et al., 2015), accounting for 12% of the average annual area burned throughout the state. Change in the rate of tundra burning projected for this century is highly uncertain (Rupp et al., 2016), but these regions appear to be particularly vulnerable to climatically induced shifts in fire activity. Modeled estimates range from a reduction in activity based on a regional process-model study of Alaska (Rupp et al., 2016) to a fourfold increase across the circumboreal region estimated using a statistical approach (Young et al., 2016).

Variability in northern fire regimes ultimately is a product of both climate and ecological controls over fuel characteristics and accumulation. Fire regime affects vegetation composition and productivity, creating the potential for fire-vegetation feedbacks to emerge that either increase or decrease fire activity at the regional scale. Although interannual variability in the fire regime is high across Alaska and western Canada, fire frequency and area burned have increased in recent years (Rupp et al., 2016). This trend is projected to continue for the rest of the century across most of this region for many climate scenarios, with the boreal region projected to have the greatest increase in total area burned (Balshi et al., 2009; Rupp et al., 2016). As fire activity increases, however, flammable vegetation, such as the black spruce forest that dominates boreal Alaska, is projected to decline as it is replaced by low-flammability deciduous forest. This shift in fuel flammability and accumulation rate could create regional-scale feedbacks that reduce the spread of fire on the landscape, even as the frequency of fire weather increases (Johnstone et al., 2011). In western Canada, by contrast, black spruce could be replaced by the even more flammable jack pine, creating regional-scale feedbacks that increase the spread of fire on the landscape (Johnson 1992). In tundra regions, graminoid (herbaceous, grass-like) tundra is projected to decrease in future climate scenarios, while flammable shrub tundra generally is projected to increase (Rupp et al., 2016). Similarly, tree migration into tundra could further increase fuel loading and flammability, creating novel fire regimes in these highly sensitive areas. Each of these scenarios has important implications for carbon release during fire.

11.1.2 Geographical Coverage

Most permafrost is located in the Northern Hemisphere, where the permafrost zone occupies 24% of the exposed land surface (22.8×10^6 km^2; Brown et al., 1998, revised February 2001; Zhang et al., 2000; see Figure 11.4, p. 435). Within the Northern Hemisphere, 47% of the permafrost zone is classified as continuous permafrost, where >90% of the land surface is underlain by frozen ground. Another 19% is classified as discontinuous permafrost, where 50% to 90% of the land surface is underlain by frozen ground. The remaining 34% of the total permafrost zone is split between sporadic and isolated permafrost, where 10% to 50% and <10% of the land surface is underlain by frozen ground, respectively. Soils in this region cover 17.8×10^6 km^2; this subset of the entire permafrost zone excludes exposed bedrock, glaciers, ice sheets, and water bodies, which, with the exception of water bodies, contain little to no organic carbon stocks (Hugelius et al., 2014). Alaska, Canada, and Greenland comprise 39% of the soil area, and Eurasia (including Russia, Mongolia, and Scandinavia) comprises 61%. The northern circumpolar permafrost zone is used for soil carbon accounting and is largely comparable to most tundra and a large fraction of the boreal biome in the Northern Hemisphere but does not overlap with them completely (see Figure 11.4). Biome regions are used for vegetation carbon accounting and cover 5×10^6 km^2 (tundra) and 12×10^6 km^2 (boreal forest), respectively (Jobbágy and Jackson 2000; Margolis et al., 2015; Neigh et al., 2013; Raynolds et al., 2012). The Tibetan plateau is outside of the geographical scope of this chapter described above. Permafrost underlays 1.35×10^6 km^2, 67% of the total plateau

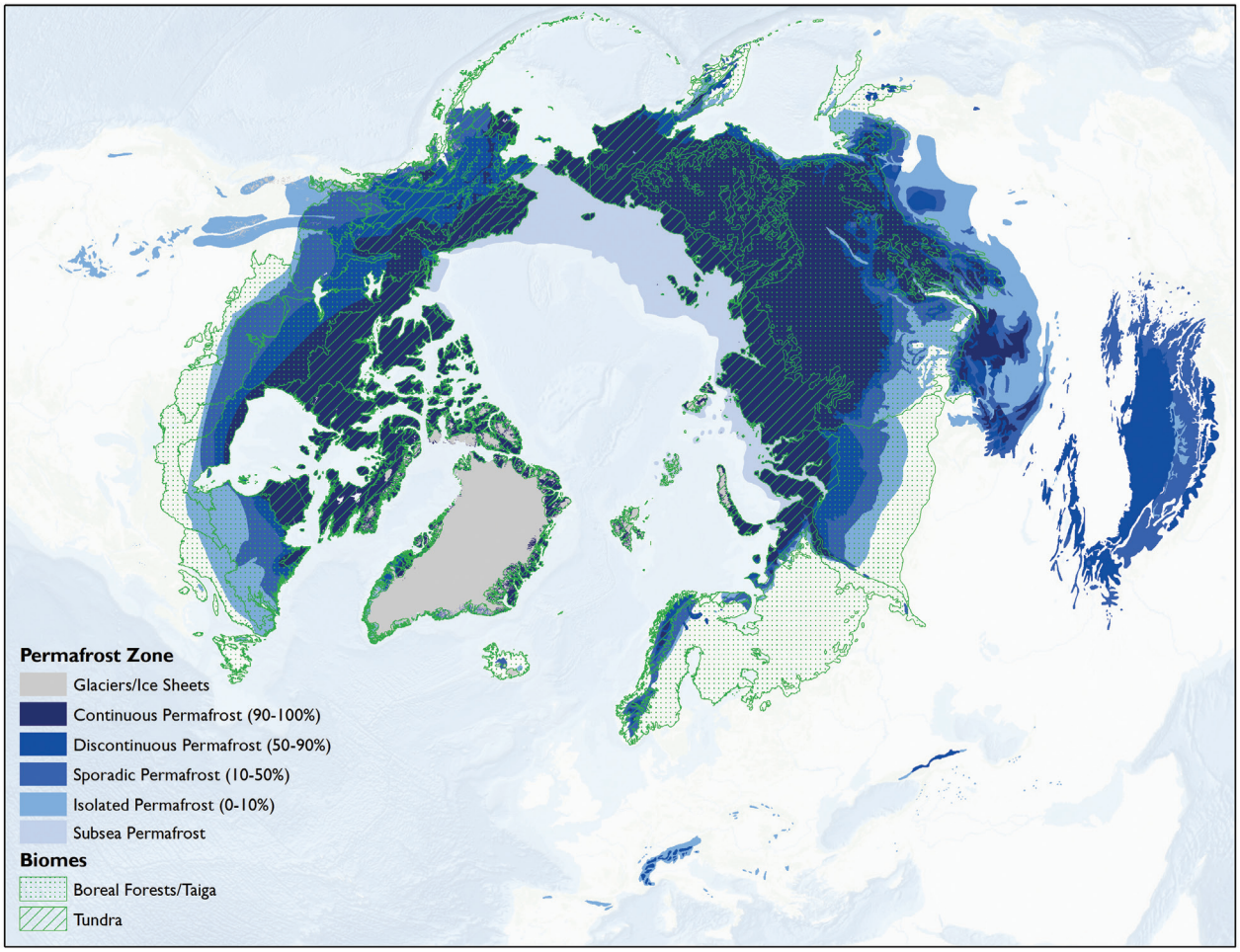

Figure 11.4. Permafrost Zones and Biome Area for Tundra and Boreal Regions. Blue areas are permafrost zones, with the legend showing percent of ground underlain by permafrost. Green dots and hashed lines define biome areas and their intersections with permafrost across some, but not all, of the region. Tundra and boreal regions outlined here are larger in area than regions quantified for carbon in this chapter, which focuses specifically on Arctic tundra and boreal forest. [Figure source: Christopher DeRolph, Oak Ridge National Laboratory. Data sources: Derived from the International Permafrost Association; Brown et al., 1997, 1998—revised February 2001; Olson et al., 2001; and World Wildlife Fund 2012.]

area, but is not classified within the tundra or boreal biome. Due to its permafrost, the soil carbon inventory is briefly discussed in this chapter in the context of the circumpolar permafrost zone soil carbon inventory.

11.1.3 Temporal Coverage

The Arctic is remote and understudied compared with more populated areas of Earth. As a result, state-of-the-art quantification of carbon pools still is being conducted for current conditions rather than as repeat measurements through time. However, a few sites have been recording time-series measurements of carbon fluxes over a few decades, although with severely restricted spatial coverage considering the large geographical scale of this domain (e.g., see Belshe et al., 2013). Observation-based changes in carbon cycling extend back to the 1970s, and this chapter focuses on historical model simulations that estimate the 50-year period from 1960 to 2009.

Forward projections typically span the time frame until 2100 using future climate projections based on emissions scenarios from the Intergovernmental Panel on Climate Change (IPCC).

11.2 Historical Context of Vegetation and Soil Carbon Pools

A unique feature of carbon pools in the northern permafrost zone compared with those in other biomes is the predominance of carbon stored in soils as a proportion of the total ecosystem carbon stock (Chapin et al., 2011). This feature partly arises from the harsh environmental conditions and short growing season that limit plant biomass. Boreal forest often is characterized by low tree density (i.e., stems per hectare) and small tree size, while tundra comprises low-statured vegetation including dwarf shrubs and graminoids with an understory of mosses (Dixon et al., 1994). Despite low plant biomass and low primary production (i.e., the amount of new carbon that plants transfer into the ecosystem annually), ecosystem carbon storage can be largely due to the tremendous quantity of carbon stored as soil organic matter. This organic matter is the remains of plants, animals, and microbes that have lived and died in these ecosystems over hundreds to thousands of years. Soil carbon accumulates in all systems (see Ch. 12: Soils, p. 469), and the overall mechanisms of soil carbon preservation are the same at high latitudes (Post et al., 1982). What makes soil carbon density particularly high in these biomes is the combination of frozen soils (either seasonally in the surface soil active layer or perennially in the permafrost) and waterlogging that restricts the resupply of oxygen below ground (Gorham 1991; Jones et al., 2017; Treat et al., 2016). Cold and water-saturated conditions reduce organic matter decomposition rates, leading to substantial soil carbon accumulation even though annual inputs of new carbon by plants is relatively low (see Figure 11.5, this page; Hobbie et al., 2000). In fact, water-saturated soils are a common feature of high-latitude ecosystems, even beyond those defined as wetlands. This saturation results from restriction of the downward movement of surface water by permafrost, creating a perched water table within the soil profile of mesic and drier upland ecosystems as well as lowland ecosystems. Waterlogged and frozen conditions slow both microbial decomposition and combustion by fire, which are primary mechanisms returning carbon from the soil back to the atmosphere. Both of these environmental conditions that slow decomposition increase in magnitude, intensity, and effect moving down into the soil profile. In addition, soil waterlogging also helps to control whether carbon returns to the atmosphere as carbon dioxide (CO_2) or methane (CH_4), both of which are important GHGs exchanged between high-latitude terrestrial ecosystems and the atmosphere.

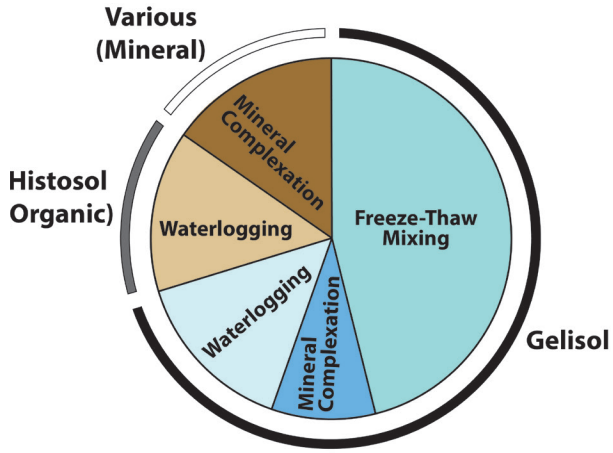

Figure 11.5. Mechanisms of Soil Carbon Stabilization Associated with Different Soil Orders in the Northern Circumpolar Permafrost Zone. Gelisol soils have a seasonally frozen active layer at the soil surface and perennially frozen (permafrost) layer at depth. Histosol and other soil orders in the permafrost zone have seasonally frozen soil at the surface. Of the Gelisol soils, freeze-thaw mixing is indicative of the Turbel suborder and waterlogging of the Histel suborder; Orthels do not have characteristics of the first two suborders. Mineral complexation and other mechanisms preserving carbon are features of all soils but are labeled here as soil orders and suborders not strongly characterized by freeze-thaw processes or waterlogging. Pie area represents proportional storage of carbon (soil depth of 0 to 3 m) in the permafrost zone. [Data source: Hugelius et al., 2014; see also Table 11.1, p. 439.]

Several features of soil development in the permafrost zone have the effect of transporting carbon from the surface (where it enters the ecosystem

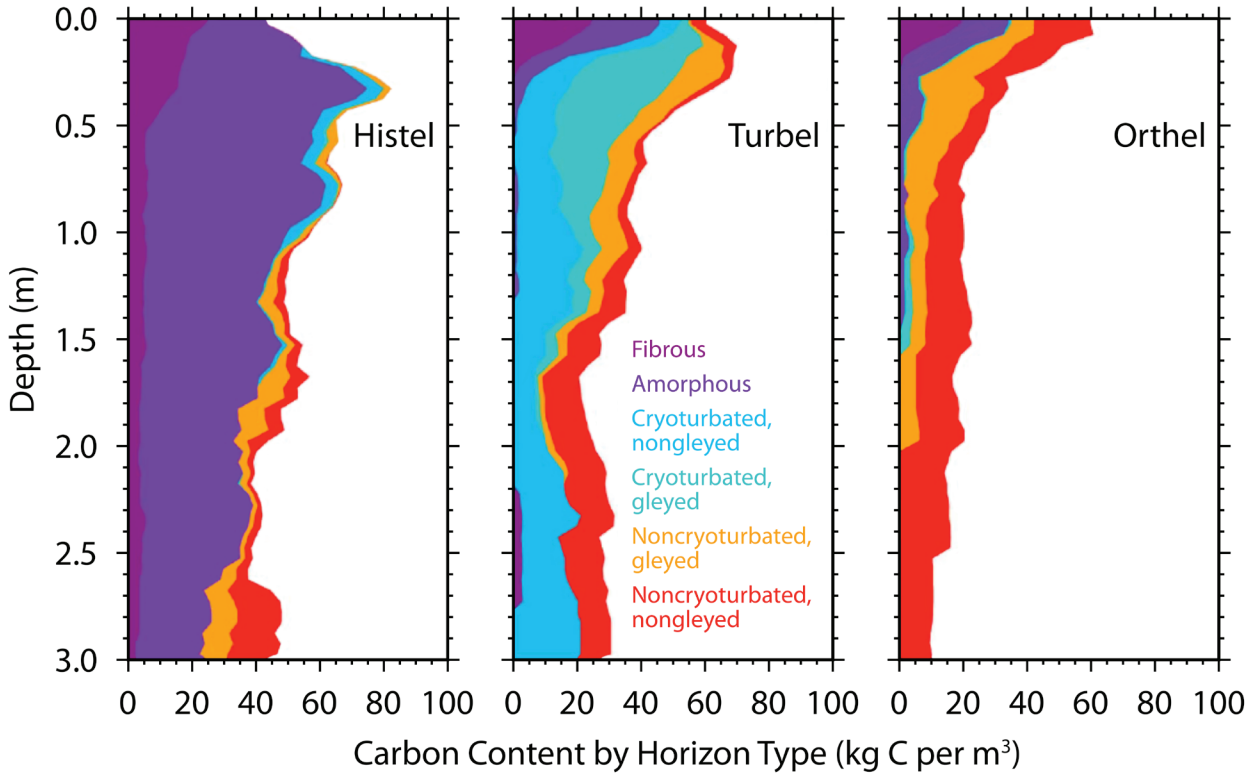

Figure 11.6. Soil Carbon Distribution in Major Suborders of the Gelisol Soil Order. Carbon in suborders Histel, Turbel, and Orthel of Gelisol (permafrost-affected soils) is shown distributed by depth and horizon type. Purple colors indicate organic horizons (>20% carbon) with less (fibrous) or more (amorphous) decomposition. Cryoturbation (freeze-thaw mixing) brings relatively carbon-rich material from the surface deeper into the soil profile. Soil horizons at depth can show evidence of periodically waterlogged (oxygen-limited) conditions (gleyed), or not (nongleyed). [Figure source: Redrawn from Harden et al., 2012, used with permission.]

through plant tissue turnover and mortality) to depth (see Figure 11.6, this page; Schuur et al., 2008). Freeze-thaw mixing (cryoturbation) occurs in permafrost soils. Cold air temperatures in the fall begin freezing soils from the surface downward, while the permafrost at depth simultaneously refreezes soils at the base of the active layer upward. This process exerts pressure on the middle soil layer that can push soil upward to release pressure through cracks to the surface. As a result, surface carbon is mixed at high concentrations deeper into the soil profile than it otherwise would have been, effectively increasing the limiting factors of temperature and waterlogging on decomposition. Another landscape-level feature of soil development that leads to relatively high carbon at depth is the upward accumulation of soil and permafrost that occurs in high latitudes, particularly regions not covered by ice during the last glacial period, which peaked roughly 20,000 years ago (Schirrmeister et al., 2002). Ice sheets covered large areas of Canada, Eurasia, and Greenland, but in Alaska, Siberia, and Beringia (i.e., the land connection between the two continents that was exposed by lower sea levels), a large swath of land remained free of ice because of dry conditions and low precipitation. These unglaciated areas received deposits of silt material generated at the margins of ice sheets and glaciers and transported by wind and water. Sediment accumulated in some areas at rates of centimeters per year, which effectively increased soil surface elevation. Permafrost depth in these soils

is controlled, in part, by the insulating effect of the overlying soil, and, with increased soil elevation, the permafrost table also moved upward, which trapped plant roots and other organic matter at depth into permafrost (Zimov et al., 2006). Additionally, these soils accumulated carbon over tens to hundreds of thousands of years, whereas ecosystems covered by ice sheets in the Last Glacial Maximum only started accumulating their current soil carbon stocks since the transition to the Holocene (Harden et al., 1992). Length of time for carbon accumulation, however, is not as important as some of the direct limits to microbial decomposition, in terms of overall soil carbon stocks. For example, large areas such as the Hudson Bay Lowlands and the Western Siberian peatlands accumulated high carbon stocks since the retreat of ice sheets in the last 10,000 years because of persistent waterlogged conditions (Smith et al., 2004; Loisel et al., 2014). Lastly, the direct human footprint on carbon pools and fluxes in this region is small relative to other biomes. More than 80% of tundra and boreal biomes fall into the land-use categories of "remote forest," "wild forest," "sparse trees," and "barren" (Ellis and Ramankutty 2008). Forest harvest is the primary land-use activity affecting ecosystem carbon, with fire management also playing a role, but both occur on a relatively small proportion of the overall region. More broadly, impacts to the region's carbon cycle more likely occur indirectly through 1) changes in climate, such as temperature, precipitation, and growing season length; 2) changes in pulse disturbances, such as wildfires, abrupt thaw, and insects; and 3) rising atmospheric CO_2, which has the potential to alter ecosystems everywhere.

11.3 Current Understanding of Carbon Pools and Fluxes

11.3.1 Soil Carbon Pools

The total pool of organic carbon stored in permafrost zone soils comprises carbon frozen at depth in peatlands (>20% carbon) and carbon mixed with mineral soils (<20% carbon). Each type dominates different locations in the Northern Hemisphere, depending on physiographic and environmental characteristics (Gorham 1991; Jobbágy and Jackson 2000; Mishra and Riley 2012; Post et al., 1982; Tarnocai et al., 2009). Recent work has shown permafrost soil carbon pools to be much larger at depth than previously recognized because of cryogenic (freeze-thaw) mixing (Bockheim and Hinkel 2007; Ping et al., 2008) and sediment deposition (Schirrmeister et al., 2002, 2011; Zimov et al., 2006). In particular, the 1.2×10^6 km^2 "yedoma" region (i.e., areas of Siberia and Alaska that remained ice-free during the last Ice Age) contains accumulated silt (loess) soils many meters thick. Even though carbon concentrations of these mineral soils are not remarkably high (0.2% to 2% carbon), the depths of these sediments give rise to large carbon inventories.

The current best estimate of total soil organic carbon (terrestrial) in the northern circumpolar permafrost zone is 1,460 to 1,600 petagrams (Pg; 1 Pg = 1 billion metric tons; Hugelius et al., 2014; Schuur et al., 2015; Strauss et al., 2017). This inventory includes all soil orders within the permafrost zone and thus also counts carbon in nonpermafrost soil orders, active-layer carbon that thaws seasonally, and peatlands. All permafrost zone soils estimated to 3 m in depth contain 1035 ± 150 Pg of carbon (C; see Table 11.1, p. 439, and Figure 11.7a, p. 440). Based on somewhat earlier estimates for the 1-m inventory, two-thirds of the soil carbon pool is in Eurasia, with the remaining one-third in North America, including Greenland (Tarnocai et al., 2009).

New synthesis reports account for 327 to 466 Pg C in deep loess (wind- and water-borne) sediment accumulations below 3 m in Siberia and Alaska (Strauss et al., 2013, 2017; Walter Anthony et al., 2014; Zimov et al., 2006; see Figure 11.7b, p. 440). This yedoma region contains both intact yedoma deposits that have remained primarily frozen since the last glacial period and deposits where abrupt thaw led to ground subsidence (thermokarst) and lake formation. These thermokarst lake deposits later refroze into permafrost when the lakes drained. The carbon density of intact yedoma is now thought to be lower than previously estimated because of revisions in soil bulk density estimates to account for excess pore ice (Schirrmeister et al., 2011).

Table 11.1. Soil Carbon Pools to 3 m in Depth for the Northern Circumpolar Permafrost Zone

Soil Orders	Soil Suborders	Soil Carbon Pool (Pg C, 0 to 3 m in depth)	Area ($\times 10^6$ km^2)
Gelisol	Turbels	476	6.2
	Orthels	98	2.5
	Histels	153	1.4
Histosol, Organic		149	0.9
Non-Gelisol, Mineral		158	6.8
Total Circumpolar		**1,035[a]**	**17.8**

Soil suborders are shown for Gelisol (permafrost soil order) only, but soil carbon (petagrams of carbon [Pg C]) in this zone also is contained in Histosol (peat soil) and non-Gelisol soil orders (various). Data are from Hugelius et al. (2014).

Notes

a) Total is different from the sum due to rounding.

In contrast, thermokarst lake deposits previously believed to have depleted soil carbon stocks are now thought to have accumulated net soil carbon (Walter Anthony et al., 2014). The discovery of increased net soil carbon as a result of the thermokarst lake cycle compensated in part for the downward revision of the carbon pool contained in intact yedoma (Strauss et al., 2013; Walter Anthony et al., 2014). The range here represents different methodologies for scaling carbon pools and also accounts for carbon remaining in thawed sediments below currently existing lakes (high estimate only).

River deltas are now thought to contain 96 ± 55 Pg C, a quantity much less than originally estimated for these deep deposits (Hugelius et al., 2014; Strauss et al., 2017; Tarnocai et al., 2009). However, other deep sediment deposits located over 5×10^6 km^2 outside the yedoma and delta areas are not included in the total soil carbon stock reported here. Simple calculations based on extremely limited data suggest that these regions may roughly contain an additional 350 to 465 Pg C, but more sampling and data synthesis are needed to verify or revise estimates of these potential deep permafrost carbon deposits (Schuur et al., 2015; see Figure 11.7b, p. 440).

Two additional pools of permafrost carbon are not included in the permafrost carbon pool summarized previously. The first are new estimates for the permafrost region of the Tibetan plateau that are built on earlier work (Wang et al., 2008), which now place 15.3 Pg C in the top 3 m of soil (Ding et al., 2016). This new carbon inventory extended deep carbon measurements substantially and used improved upscaling techniques, resulting in a somewhat smaller inventory for Tibetan permafrost than had been reported previously (Mu et al., 2015). An additional 20.4 Pg C are contained in 1-m inventories of permafrost soils in northern China estimated by earlier first-order inventories (Luo et al., 2000) for a total of 35.7 Pg C for this region as a whole.

The second uncounted pool is a reservoir of organic carbon in permafrost stored on the continental shelf under the Arctic Ocean (Brown et al., 1998—revised February 2001; Rogers and Morack 1980). This undersea permafrost carbon initially formed on land as the continental shelf was exposed when sea level was approximately 120 m lower during the last glacial period (Walter et al., 2007). Subsequent inundation of this area at the Pleistocene-Holocene transition started thawing this loess permafrost (Rachold et al., 2007). No reliable published estimates exist for the total organic carbon in this subsea pool (setting aside inorganic CH_4 clathrates), but yedoma deposits are thought to have covered much

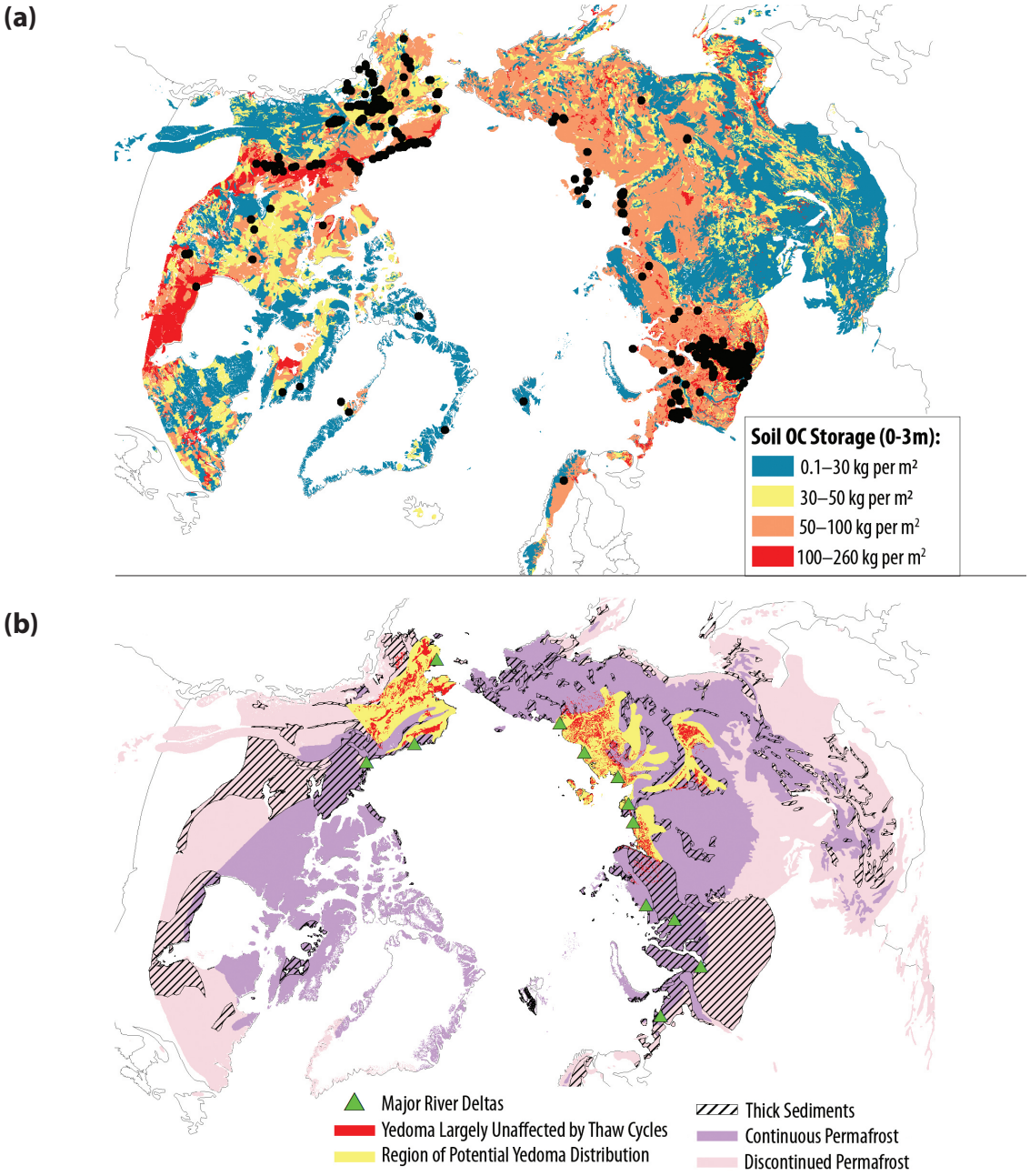

Figure 11.7. Soil Organic (SOC) Carbon Maps. (a) The SOC pool in kg of carbon per m^2 contained in the interval of 0 to 3 m in depth of the northern circumpolar permafrost zone. Black dots show field site locations for carbon inventory measurements of 0 to 3 m. **(b)** Deep permafrost carbon pools (>3 m), including the location of major permafrost-affected river deltas (green triangles); extent of the yedoma region previously used to estimate the carbon content of these deposits (yellow); current extent of yedoma-region soils largely unaffected by thaw-lake cycles that alter original carbon content (red); and extent of thick sediments overlying bedrock (black hashed). Yedoma regions generally are also thick sediments. The base map layer shows permafrost distribution with continuous regions to the north having permafrost everywhere (>90%, purple shading) and discontinuous regions further south having permafrost in some, but not all, locations (<90%, pink shading). [Figure source: Reprinted from Schuur et al., 2015, copyright Macmillan Publishers Ltd, used with permission.]

of the shallow shelf during its exposure. Although there are no shelf carbon inventories comparable to those for land, the shallow shelf area exposed as dry land in the area around Alaska and Siberia during the last Ice Age (currently 125 m deep in the ocean) is almost 3×10^6 km^2, or about 2.5 times the size of the current terrestrial yedoma region (Brosius et al., 2012; Strauss et al., 2013). At the same time, submergence over thousands of years helped thaw permafrost, exposing organic carbon to decomposition, potentially under anaerobic conditions. These processes and conditions would have converted a portion of the carbon pool to CO_2 and CH_4, leaving an unknown quantity of organic carbon remaining in both the sediment and the permafrost that persists under the ocean.

Soils in the top 3 m of the rest of Earth's biomes (excluding Arctic and boreal biomes) contain 2,050 Pg organic carbon (Jobbágy and Jackson 2000). The soil carbon quantified here from the northern circumpolar permafrost zone adds another 50% to this 3-m inventory, even though it occupies only 15% of the total global soil area (Schuur et al., 2015). Making this comparison with deposits deeper than 3 m (such as those in yedoma) is difficult because deeper deposits are not always as systematically quantified in soil carbon inventories outside the permafrost zone. Assuming that permafrost has preserved deep carbon stocks at higher levels than elsewhere on Earth, the proportion of total soil carbon contained in the northern circumpolar permafrost region could be even larger.

11.3.2 Vegetation Carbon Pools

Most carbon stored in the vegetation of northern high latitudes is in boreal forests, which account for one-third of global forests (Pan et al., 2011). Nonsoil carbon pools of the boreal forest consist of deadwood, litter, and above- and belowground live biomass (Pan et al., 2011). The boreal zone, generally defined by latitudes between 45°N and 70°N (Margolis et al., 2015; McGuire et al., 2009; Neigh et al., 2013), is characterized by tundra at the northern boundary and temperate forest, steppe, or prairie at the southern boundary (see Figure 11.4, p. 435). Spruce, pine, and fir are typical coniferous tree species within the boreal zone mixed with deciduous species of larch, birch, alder, and aspen (Neigh et al., 2013). The North American boreal zone spans a total area of 3.73×10^6 km^2, which is one-third of the entire circumpolar boreal zone (11.35×10^6 km^2 to 11.93×10^6 km^2; see Table 11.2, p. 442; Neigh et al., 2013; Pan et al., 2011). Biomass estimates for boreal forests mostly exclude root biomass because it is not measured in many inventories. This chapter uses a ratio of 0.27 for root-to-total phytomass (Saugier et al., 2001) and calculates total carbon pools for the boreal zone (see Table 11.2). Numbers are presented for Alaska, eastern and western Canada, and the circumpolar North using the aboveground biomass values reported in Margolis et al. (2015) and Neigh et al., (2013), which combine satellite light detection and ranging (LIDAR), airborne LIDAR, and ground plot estimates.

Half the carbon in Alaska and Canada's boreal zone is stored in coniferous forests; this is also true for the entire circumpolar region (7.66 Pg C in North America; see Table 11.2, p. 442). The second largest forest type is "mixed wood" (i.e., coniferous and deciduous trees) followed by "hardwood" (i.e., deciduous trees), which together account for 35% to 42% of the total boreal vegetation carbon stocks. A small portion of vegetation carbon in the boreal zone is found in the biomass of wetlands (5% to 12%) and in burned areas (about 1%). A separate synthesis reported 14.0 Pg C for all living biomass (both above and below ground) in Canada, covering 2.29×10^6 km^2; Pan et al., 2011). Estimates for that synthesis were based on forest inventory data; growth and yield data; and data on natural disturbances, forest management, and land-use change. Because forest inventory data were used, areas covering 1.18×10^6 km^2 of unmanaged boreal forest in Canada and 0.51×10^6 km^2 of unmanaged forest in Alaska were excluded, but, in general, the stock-based carbon numbers are similar to the remotely sensed estimates for Canada and the circumpolar North. Discrepancies in carbon pools could arise from different measurement approaches and the known limitations of satellite-based LIDAR measurements in steep topography (Margolis et al., 2015).

Table 11.2. Vegetation Carbon Pools for North America and Global Northern High-Latitude Regions

Vegetation Type	Region/Ecosystem	Vegetation Carbon Pool (Pg C)	Area ($\times 10^6$ km^2)
Boreal Forest	**Alaska**		
	Wetlands	0.09	0.06
	Hardwood	0.3	0.05
	Conifer	0.79	0.21
	Mixed Wood	0.24	0.05
	Burned	0.02	0.01
	Total Alaska	**1.51**	**0.37**
	Canada		
	Wetlands	1.61	0.78
	Hardwood	1.84	0.27
	Conifer	6.87	1.7
	Mixed Wood	3.05	0.53
	Burned	0.14	0.04
	Total Canada	**13.56**	**3.36**
	Circumboreal		
	Wetlands	2.21	1.25
	Hardwood	2.44	0.37
	Conifer	27.6	7.28
	Mixed Wood	19.26	2.84
	Burned	0.48	0.18
	Total Circumboreal	**52.05**	**11.93**
Tundra	*Alaska*	0.35	0.48
	Canada	1.01	2.34
	Total Circumpolar[a]	**3.17**	**4.98**

Boreal forest vegetation carbon includes carbon in above- (Neigh et al., 2013) and belowground live biomass. Belowground numbers were calculated based on root–to–total biomass ratios (after Saugier et al., 2001). Ratios are 0.27 for boreal forests and 0.62 for tundra biomass. Tundra area data exclude ice caps and large water bodies (Raynolds et al., 2012). Estimates for deadwood carbon and litter carbon pools are reported in the main chapter text. Totals are reported from the original publication (Neigh et al., 2013) and, in some cases, may not match the component sums exactly due to rounding differences.

Notes

a) Total circumpolar also includes estimates for Eurasia (data not shown). Eurasia quantities are equivalent to the total minus the estimates for Alaska and Canada.

The Arctic tundra vegetation zone is north of the boreal tree line, extending all the way above 80°N latitude in the Canadian High Arctic and is described in detail in the circumpolar Arctic vegetation map (see Figure 11.4, p. 435; Walker et al., 2009). Recent estimates quantified a total vegetated area of 4.98×10^6 km^2 in the circumpolar tundra zone, of which a little less than half is in Canada and about 10% in Alaska (see Table 11.2, this page; Raynolds et al., 2012). Tundra vegetation mostly consists of

shrubland, peaty graminoid tundra, mountain complexes, barrens, graminoid tundra, prostrate shrubs, and wetlands (Walker et al., 2009). Using a relationship of aboveground biomass and the normalized difference vegetation index (NDVI), the North American tundra zone is estimated to contain 1.03 Pg C in aboveground plant biomass (0.27 Pg C in Alaska and 0.76 Pg C in Canada; Raynolds et al., 2012). Assuming that 62% of the total tundra biomass is below ground (Saugier et al., 2001) and half the biomass is carbon (Epstein et al., 2012), there is a total carbon stock of 1.36 Pg C contained in North American tundra vegetation (see Table 11.2, p. 442). For the entire circumpolar region, this amount is equal to 3.17 Pg C. There is an offset in land area between the soil carbon and vegetation carbon estimates of 0.89×10^6 km^2, which is likely either non-Arctic (sub-Arctic or alpine) tundra or sparse conifer forest (taiga). Using tundra carbon pools as a low-end estimate, there could be another 0.57 Pg C in vegetation biomass contained on these lands but not reported in Table 11.2.

Earlier estimates for vegetation carbon in northern high latitudes reported 5 Pg C in Alaska, 12 Pg C in Canada, and 60 to 70 Pg C for the circumpolar North (McGuire et al., 2009). Although previous carbon estimates for Canada and the circumpolar North are relatively similar to the new remotely sensed and inventoried estimates reported here, the 5 Pg C estimate for Alaska is higher. Combining the latest boreal and tundra vegetation estimates, North American high-latitude areas, which are 30% of the entire circumpolar region, contain 16.43 Pg C in vegetation (15.07 Pg C boreal; 1.36 Pg C tundra).

Deadwood and litter are two nonsoil carbon pools poorly constrained by data at regional and continental scales. The deadwood pool has been estimated (in 2007) at 16.1 Pg C for a region of the boreal forest covering 11.35×10^6 km^2, again excluding 1.18×10^6 km^2 of unmanaged boreal forest in Canada and 0.51×10^6 km^2 of unmanaged forest in Alaska (Pan et al., 2011). This same boreal region was estimated to contain a litter carbon pool of 27.0 Pg C, which together with deadwood represents at least 83% of the carbon contained in the living above- and belowground biomass. An older modeling study estimated tundra litter to contribute 2 Pg C at the circumpolar scale (Potter and Klooster 1997).

11.4 Indicators, Trends, and Feedbacks

11.4.1 Drivers of Carbon Pool Change

Changes in soil and vegetation carbon pools are a result of changing carbon fluxes over time. In the absence of pulse disturbances, CO_2 exchange between ecosystems and the atmosphere is the major pathway of carbon input and output (Chapin et al., 2006). Carbon dioxide enters ecosystems via plant photosynthesis and is returned to the atmosphere through respiration of plants and all heterotrophic organisms that depend directly or indirectly on energy contained in plant biomass. Over the past few centuries to millennia, tundra and boreal ecosystems acted as net carbon sinks at the regional scale, as the amount of carbon released by respiration was smaller than that absorbed by photosynthesis. Vegetation biomass is likely to have reached peak amounts over decades to perhaps a century or more. In contrast, soils act as a long-term (i.e., century to millennia) carbon sink as carbon continues to accumulate as dead organic matter (Harden et al., 1992). Carbon accumulation resulting from the net difference between photosynthesis and respiration also is punctuated by periods of abrupt loss catalyzed by ecological disturbances. In the tundra and boreal biomes, large-scale pulse disturbances include fire, insect outbreaks, and abrupt permafrost thaw and soil subsidence (known as thermokarst). Periods of disturbances generally favor carbon losses either abiotically (e.g., fire emissions) or biotically (e.g., stimulating respiration). These losses often occur as a pulse loss, whereas carbon gains through vegetation growth and succession and new soil carbon accumulation occur over decadal to century timescales. Other smaller but important carbon fluxes in high-latitude ecosystems include CH_4 flux and the lateral export of dissolved inorganic carbon (DIC), dissolved organic carbon (DOC), and particulate organic carbon (POC) in water (McGuire et al., 2009). Methane flux by weight is usually an

order of magnitude smaller than CO_2 flux but has a higher global warming potential (GWP). Dissolved carbon losses are a persistent feature of undisturbed and disturbed ecosystems and also are typically an order of magnitude smaller than CO_2 exchanges. An exception is POC, which usually is similar in magnitude to other dissolved losses and relatively small in many circumstances. However, it is the one flux that can approach the magnitude of CO_2 exchanges, at least for short periods, when erosion is a consequence of another disturbance such as abrupt permafrost thaw or fire.

11.4.2 Carbon Fluxes in Recent Decades

Stock Changes

Changes in vegetation and soil carbon stocks over time provide an estimate of landscape carbon budgets. For boreal and Arctic ecosystems, the challenge is that study sites are remote and often not spatially representative. Inventories of aboveground plant biomass in forests are probably the best measured of all ecosystem carbon pools, along with harvested wood products (i.e., managed forests) and then deadwood. Rather than estimated through time, belowground biomass, litter, and soil stocks usually are estimated from single time-point measurements and extrapolated using simple scaling assumptions. The most recent regional estimates for Eurasian and Canadian boreal forests put total carbon flux (total of all pools described above) at 493 ± 76 teragrams (Tg) C per year from 1990 to 1999 and at 499 ± 83 Tg C per year from 2000 to 2007 (Pan et al., 2011). These estimates do not include forestland in interior Alaska (0.51×10^6 km^2) or unmanaged forests in northern Canada (1.18×10^6 km^2), essentially assuming those lands to be at steady state in regard to carbon pools.

Carbon Dioxide

Recent syntheses have outlined changes in tundra carbon flux over time. A broad survey of data from a number of dry to wet tundra types found that in most studies since 1995, tundra acts as a carbon sink during summer, when photosynthetic uptake exceeds respiration losses during this approximately 100-day season (McGuire et al., 2012). Summer carbon sequestration is offset partially by carbon losses in fall, winter, and spring when microbes are still metabolically active and releasing CO_2, while plants are largely dormant and carbon assimilation has slowed or ceased. While absolute levels of CO_2 flux are low during the nonsummer season, the long period of more than 250 days is enough to offset, in some cases, the net carbon that accumulated during summer. A critical issue for determining net change in ecosystem carbon storage is the relative scarcity of nonsummer flux measurements in comparison to summer flux measurements. For example, the recent regional carbon balance estimate for the North American subregion had 80 study-years of summer measurements and only 9 study-years of nonsummer measurements available for upscaling (McGuire et al., 2012). This order of magnitude difference across seasons was similar across the other upscaled tundra subregions.

A first-order upscaling synthesis that used plot-scale measurements scaled by regional land area showed that North American tundra was a source of carbon on the order of 124 Tg C per year during the 1990s and a sink of 13 Tg C per year during the 2000s (McGuire et al., 2012). This increase in uptake relative to losses was similar to that in the Eurasian tundra that was reported as a 19 Tg C per year source in the 1990s and a sink of 185 Tg C per year in the 2000s. This study reported a global carbon exchange in the tundra region of 13 Tg C per year (i.e., a small sink but near neutral exchange) over both decades using a scaling region of 9.2×10^6 km^2, which includes the tundra biome plus a portion of the boreal forest biome for comparison to large-scale atmospheric inversion models. A follow-up synthesis study focused on a subset of the same tundra sites and also included new sites with nonsummer data to bolster undersampled seasons (Belshe et al., 2013). Although this analysis supported the previous finding that the summer-season carbon sink increased in the 2000s compared with the 1990s, it suggested that the mean tundra flux remained a carbon source annually across both decades when additional nonsummer flux data were included. In this analysis,

the source potential appears to decline over time, although this decline is statistically nonsignificant. Separately analyzing the record for the nonsummer data-intensive period (2004 to 2010) showed a trend of increasing nonsummer carbon flux and an overall increase in tundra carbon source during that period. Because changes in measurement technology parallel trends in time, data also were analyzed relative to the mean annual temperatures of the study sites. The trend of tundra consistently acting as an annual carbon source was significant across the range of tundra sites, with the net loss ranging from 23 to 56 grams (g) C per m^2 per year. This relationship also predicts a 2 g C per °C increase in loss rates across the range of mean annual temperatures. These figures, when scaled to a region consistent with the previous study (10.5×10^6 km^2; Callaghan et al., 2004; McGuire et al., 1997, 2012), predict that the tundra is acting as current source of 462 Tg C per year that could increase by almost 35% to 620 Tg C per year, given the "business-as-usual" warming projected for the Arctic (i.e., an increase of 7.5°C).

Recent measurements of atmospheric GHG concentrations over Alaska have been used to estimate carbon source and sink status of those Arctic and boreal ecosystems for 2012 to 2014 (Commane et al., 2017). During this period, tundra regions of Alaska were a consistent net CO_2 source to the atmosphere, whereas boreal forests were either neutral or a net CO_2 sink. The larger interannual variability of boreal forests was due both to changes in the balance of photosynthesis and respiration and to the amount of combustion emissions by wildfire. The Alaska study region as a whole was estimated to be a net carbon source of 25 ± 14 Tg C per year averaged over the land area of both biomes for the entire study period. If this Alaskan region (1.6×10^6 km^2) was representative of the entire northern circumpolar permafrost zone soil area (17.8×10^6 km^2), this amount would be equivalent to a region-wide net source of 0.3 Pg C per year.

Methane

Uncertainty in the scaling of "bottom-up" field-based flux observations of CH_4 emissions across the northern permafrost region (32 to 112 Tg CH_4 per year; McGuire et al., 2009) is much larger than uncertainty from "top-down" atmospheric analyses based on the spatial and temporal variability of CH_4 concentration measurements (15 to 50 Tg CH_4 per year; McGuire et al., 2009; Crill and Thornton 2018). Flux estimates include those from terrestrial ecosystems (e.g., wetlands), lakes, and coastal waters underlain by permafrost. Observational studies reviewed by McGuire et al. (2012) indicate that during the 1990s and 2000s, the tundra emitted 14.7 Tg CH_4 per year (with an uncertainty range of 0 to 29.3 Tg CH_4 per year). Kirschke et al. (2013) suggest a Eurasian boreal wetland source of 14 Tg CH_4 per year (uncertainty = 9 to 23) from field flux measurements and 9 Tg CH_4 per year (uncertainty = 4 to 13) from atmospheric measurements, which also estimate an upland soil sink of 3 Tg CH_4 per year (uncertainty = 1 to 5). For North American high-latitude wetlands, estimated emissions are 9 Tg CH_4 per year (uncertainty = 6 to 17) from atmospheric measurements and 16 Tg CH_4 per year (uncertainty = 9 to 28) from field flux measurements, along with a soil sink of 2 Tg CH_4 per year (uncertainty = 1 to 2) estimated from atmospheric measurements. The most recent assessment reports that the field flux uncertainty in CH_4 emissions from tundra terrestrial ecosystems and lakes in the Arctic was between 10 and 43 Tg CH_4 per year during the 1990s and 2000s (AMAP 2015). This estimate indicates that bottom-up uncertainties have not been reduced by more recent assessments. Estimates of CH_4 fluxes from lakes likely are confounded with those from wetlands in spatial scaling procedures. A recent synthesis that focused just on lakes in the northern permafrost region indicates that CH_4 emissions from lakes range from 6 to 25 Tg CH_4 per year (Walter Anthony et al., 2016; Wik et al., 2016). Also, there are large uncertainties about the magnitude of CH_4 emitted from submarine permafrost in coastal waters of the Arctic Ocean and its marginal seas (Berchet et al., 2016; Shakhova et al., 2010, 2014). The degree to which the source of CH_4 emissions in coastal waters results from biogenic methanogenesis, fossil sources, or the dissociation of gas hydrates

is not clear. The amount of CH_4 emitted from fossil sources is an issue for both land and ocean environments in the permafrost region. Emissions include CH_4 from natural sources such as geological seeps and human activities, including oil and gas exploration and transport (Ruppel and Kessler 2017; Kohnert et al., 2017). Top-down estimates of CH_4 emissions from the permafrost region are useful because they integrate the various sources of CH_4 to the atmosphere. However, these top-down flux estimates also have substantial uncertainties because they are derived from models, which still need to be better reconciled with field flux measurements.

Recent developments include increased use of atmospheric measurements from aircraft, which have the great advantage of avoiding biases induced by logistical constraints on ground-based study site selections or "hotspot"-focused studies that ignore potentially vast areas of CH_4 uptake (e.g., 3.2 ± 1.4 mg CH_4 per m^2 per day in dry tundra and 1.2 ± 0.6 mg CH_4 per m^2 per day in moist tundra in northeast Greenland; Juncher Jørgensen et al., 2015). Aircraft atmospheric measurements also inherently include previously neglected freshwater systems estimated to contribute as much as 13 Tg CH_4 per year north of 54°N (Bastviken et al., 2011). A recent study used aircraft concentration data and inverse modeling to derive regional fluxes averaged over all of Alaska amounting to 2.1 ± 0.5 Tg CH_4 from May to September 2012 (Chang et al., 2014). This quantity includes all biogenic, anthropogenic, and geological sources such as seeps, which alone contribute an estimated 1.5 to 2 Tg CH_4 per year (Walter Anthony et al., 2012), based on extrapolating ground-based measurements.

Spatial analyses of CH_4 emissions in the northern permafrost region indicate that "wetter" wetlands are primarily sensitive to variation in soil temperature, whereas "drier" wetlands are primarily sensitive to changes in water-table position (Olefeldt et al., 2013). Similar analyses for lakes indicate that in systems with suitable organic substrate, CH_4 emissions are sensitive to water temperature, particularly in the continuous permafrost zone (Wik et al., 2016). In addition, some studies have proposed that seasonality of CH_4 emissions is potentially sensitive to ongoing climate change, with emissions possibly persisting further into fall as soils remain unfrozen for longer periods (Mastepanov et al., 2008; Miller et al., 2016; Zona et al., 2016) or elevating in spring as CH_4 is released from trapped pockets in the frozen soil (Raz-Yaseef et al., 2016). These sensitivities suggest that observed changes in temperature of the northern permafrost region should have resulted in increased CH_4 emissions (Walter Anthony et al., 2016), and modeling studies that have incorporated these sensitivities conclude this as well (Riley et al., 2011; Xu et al., 2016). However, while temperature has increased substantially in the northern permafrost region in recent decades, there is no indication from analyses of atmospheric data that CH_4 emissions in the region have increased (Bergamaschi et al., 2013; Bruhwiler et al., 2014; Dlugokencky et al., 2009; Sweeney et al., 2016). The lack of significant long-term trends suggests more complex biogeochemical processes may be counteracting the observed short-term temperature sensitivity (Sweeney et al., 2016). Alternatively, separating biogenic changes in northern ecosystems from fossil-fuel derived emissions from lower latitudes may be difficult using surface atmospheric concentration measurements alone (Parazoo et al., 2016).

Lateral Hydrologic Losses

Carbon can move laterally into inland waters from terrestrial upland and wetland ecosystems in Arctic and boreal biomes. In inland waters, carbon derived from living and dead organic matter is transported largely to the ocean as DOC, DIC, and POC (see Ch. 14: Inland Waters, p. 568). The annual export of carbon from rivers to the Arctic Ocean is estimated to be 43 Tg C as DIC, 33 Tg C as DOC, and 6 Tg C as POC, for a total of 82 Tg C per year (McGuire et al., 2009). A recent assessment for Alaska estimates that the riverine flux of DIC, DOC, and POC to the ocean is 18 to 25 Tg C per year (Stackpoole et al., 2016), representing 22% to 30% of the total riverine flux of carbon to the Arctic Ocean estimated by McGuire et al. (2009). Although this percentage of

the total appears large for Alaska relative to its small geographic discharge area, it may indicate that earlier estimates were too low (McGuire et al., 2009).

Coastal erosion in the Arctic is an important source of POC to the Arctic Ocean, and this flux is likely to increase with warming because of enhanced erosion associated with the loss of a protective sea ice buffer, increasing storm activity, and thawing of coastal permafrost (e.g., Jorgenson and Brown 2005; Rachold et al., 2000, 2004). Based on recent estimates (Rachold et al., 2004), POC transport across the Arctic land-ocean interface through coastal erosion is about 6 to 7 Tg C per year (McGuire et al., 2009).

Fire

Fire has the largest footprint of any pulse disturbance in the northern circumpolar permafrost zone; thus, increases in the size, frequency, and severity of regional fire regimes will have important impacts on current and future carbon stocks and fluxes (Balshi et al., 2009; Bond-Lamberty et al., 2007; Kasischke et al., 1995). At the ecosystem scale, fire catalyzes abrupt changes in stocks by transferring carbon from plants and soils to the atmosphere. In contrast to temperate and tropical wildfires, soil organic matter is the dominant source of carbon emissions from boreal and tundra wildfires, and fire-driven changes in soil structure can alter controls over ecosystem carbon dynamics such as ALT, hydrology, and vegetation age and composition. At the landscape scale, increasing fire activity will alter the age structure of forests and tundra, decreasing landscape carbon stocks and increasing or, perhaps less frequently, decreasing carbon sequestration (Yue et al., 2016).

Estimates of carbon emissions from global boreal forest fires averaged 155 Tg C per year (with a range of 78 to 334 Tg C per year) from 1997 to 2013 (Giglio et al., 2013; van der Werf et al., 2010). North American boreal forests contributed 7% to 79% of these emissions and averaged 30%, which is similar to their proportional area (see Table 11.2, p. 442). However, recent extreme fire years (2014 in northern Canada and 2015 in Alaska) doubled emissions from this region to about 100 Tg C per year, similar to average emissions from the much larger Eurasian boreal region. Extreme fire years are common in both regions. For example, within the last 19 years, North American boreal forests had 6 years where emissions were double the long-term average of 56 Tg C per year, and boreal Eurasian forests had 3 years with emissions double the long-term average of 106 Tg C per year. In contrast to the boreal forest, global carbon emissions from tundra wildfires are poorly constrained, but, on a per-unit-burned-area basis, tundra emissions can be similar in magnitude to boreal forest emissions because of the deep burning of organic soils (Mack et al., 2011). This finding suggests that increased tundra burning will have a similar per-unit-area impact to increased boreal forest burning.

Regional patterns of changing fire severity are less understood than changes in area. Increases in fire frequency are important because they reduce carbon recovery time post-fire and make forests more vulnerable to high-intensity fires (Hoy et al., 2016) or shifts in vegetation dominance (Brown and Johnstone 2012). In permafrost-affected soils, a large quantity of organic carbon resides in a thick soil organic layer that can be hundreds to thousands of years old; this carbon is a legacy of past fire cycles (Harden et al., 2000). Combustion of the soil organic layer dominates carbon emissions during fires (Boby et al., 2010; Kasischke et al., 1995; Mack et al., 2011), and more severe fires result in deeper burning (Turetsky et al., 2011a). Because soil carbon accumulation rates vary across the landscape (Hobbie et al., 2000), deeper burning may not always combust legacy carbon (Mack et al., 2011), but when it does, this burning could rapidly shift ecosystems across a carbon cycling threshold, from net accumulation of carbon from the atmosphere over multiple fire cycles to net loss (Turetsky et al., 2011b).

Fires that burn deeply into the soil organic layer can persistently alter both physical and biological controls over carbon cycling, including permafrost stability, hydrology, and vegetation. Reduction or loss of the soil organic layer decreases ground insulation (Jiang et al., 2015; Jorgenson 2013; Jorgenson et al.,

2013; Shur and Jorgenson 2007), warming permafrost soils and exposing organic matter that has been frozen for hundreds to thousands of years to microbial decomposition, mineralization, and atmospheric release of GHGs (Schuur et al., 2008). Permafrost degradation also can increase or decrease soil drainage, leading to abrupt changes in soil moisture regimes that affect both decomposition and production (Jorgenson 2013; Jorgenson et al., 2013; Schuur et al., 2009). These changes sometimes lead to abrupt permafrost thaw and thermal erosion events that drive further change in ecosystem processes. In addition, loss of the soil organic layer exposes mineral soil seedbeds (Johnstone et al., 2009), leading to recruitment of deciduous tree and shrub species that do not establish on organic soil (Kasischke and Johnstone 2005). This recruitment has been shown to shift post-fire vegetation to alternate successional trajectories (Johnstone et al., 2010). Model projections suggest that the Alaskan boreal forest could cross a tipping point, where recent increases in fire activity have made deciduous stands as abundant as spruce stands on the landscape (Mann et al., 2012). In Arctic *Larix* forests of northeastern Siberia, increased fire severity can lead to increased tree density in forested areas and forest expansion into tundra (Alexander et al., 2012). Additionally, burned graminoid tundra has been observed to increase in post-fire greenness (Hu et al., 2015), an occurrence that has been linked to increased tall deciduous shrub dominance (Racine et al., 2004; Rocha et al., 2012). Plant-soil-microbial feedbacks within new vegetation types determine long-term trajectories of nutrient dynamics (Melvin et al., 2015) that, in turn, constrain ecosystem carbon storage (Alexander and Mack 2016; Johnstone et al., 2010) and resultant climate feedbacks via carbon and energy (Randerson et al., 2006; Rocha et al., 2012).

11.4.3 Future Vulnerabilities

Carbon in Arctic and boreal ecosystems is expected to be subject both to press disturbances such as increasing temperatures, changing precipitation regimes, and rising CO_2 and to pulse disturbances including wildfire, insect outbreaks, and abrupt permafrost thaw. Rates of both disturbance types may change over time depending on future human activities and the resulting ecosystem- and landscape-level feedbacks. No single future assessment technique includes all these mechanisms comprehensively. This section provides estimates of carbon pool change using three different assessment techniques: 1) semiquantitative assessment that relied on expert knowledge of the system; 2) dynamical models that relied on environmental input data and knowledge of underlying mechanistic relationships of ecosystem dynamics; and 3) upscaling of laboratory measurements of potential soil carbon change.

Expert Assessment

To provide an integrated assessment of the effect of environmental changes in combination with heterogeneity in permafrost decomposability across the region, experts were asked to provide quantitative estimates of permafrost carbon change in response to four scenarios of warming (Schuur et al., 2013). For the highest warming scenario (RCP8.5), experts hypothesized that carbon release from permafrost zone soils could be 19 to 45 Pg C by 2040, 162 to 288 Pg C by 2100, and 381 to 616 Pg C by 2300 in CO_2 equivalent[1] using a 100-year CH_4 GWP. The values become 50% larger using a 20-year CH_4 GWP, with one-third to one-half of expected climate forcing coming from CH_4, even though it accounted for only 2.3% of the expected carbon release. Experts projected that two-thirds of this release could be avoided under the lowest warming scenario (RCP2.6; Schuur et al., 2013). According to the experts, changes in tundra and boreal vegetation biomass were smaller, totaling an increase of about 15 Pg C by 2100 under the highest warming scenario (RCP8.5; Abbott et al., 2016). In contrast to soil, assessment of biomass change was more divergent among experts, with one-third of respondents predicting either no change, or even

[1] Carbon dioxide equivalent (CO_2e): Amount of CO_2 that would produce the same effect on the radiative balance of Earth's climate system as another greenhouse gas, such as methane (CH_4) or nitrous oxide (N_2O), on a 100-year timescale. For comparison to units of carbon, each kg CO_2e is equivalent to 0.273 kg C (0.273 = 1/3.67). See Box P.2, p. 12, in the Preface for more details.

a decrease, in biomass over all time intervals and warming scenarios that were considered.

Model Projections

A number of ecosystem models and ESMs have incorporated a first approximation of global permafrost carbon dynamics. Recent key improvements include the physical representation of permafrost soil thermodynamics and the role of environmental controls (particularly the soil freeze-thaw state) in organic carbon decomposition (Koven et al., 2011, 2013; Lawrence et al., 2008). These improved models specifically address processes known to be important in permafrost ecosystems but were missing from earlier model representations. They have been key to forecasting the potential release of permafrost carbon with warming and the impact this release would have on the rate of climate change. Model scenarios show potential carbon release from the permafrost zone ranging from 37 to 174 Pg C by 2100 under the current climate warming trajectory (RCP8.5), with an average across models of 92 ± 17 Pg C (mean ± standard error [SE]); Burke et al., 2012, 2013; Koven et al., 2011; MacDougall et al., 2012; Schaefer et al., 2011; Schaphoff et al., 2013; Schneider von Deimling et al., 2012; Zhuang et al., 2006). This range is generally consistent with several newer, data-driven modeling approaches that estimated soil carbon releases by 2100 (for RCP8.5) to be 57 Pg C (Koven et al., 2015) and 87 Pg C (Schneider von Deimling et al., 2015), as well as an updated estimate of 102 Pg C from one of the previous models (MacDougall and Knutti, 2016). Furthermore, thawing permafrost carbon is forecasted to affect global climate for centuries. Models that projected emissions further out into the future beyond 2100 estimated additional carbon releases beyond those reported above. More than half of eventual total permafrost carbon emissions projected by the models, on average, would occur after 2100. While carbon releases over these time frames are understandably uncertain, they illustrate the momentum of a warming climate that thaws near-surface permafrost, causing a cascading release of GHGs, as microbes slowly decompose newly thawed permafrost carbon. The latest model simulations performed either with structural enhancements to better represent permafrost carbon dynamics (Burke et al., 2017) or with common environmental input data (McGuire et al., 2016) show similar soil carbon losses. However, they also indicate the potential for stimulated plant growth (e.g., with increased nutrients, temperature and growing season length, and CO_2 fertilization) to offset some or all of these losses by sequestering new carbon into plant biomass and increasing inputs into the surface soil (McGuire 2018).

Within the wide uncertainty of forecasts, some broader patterns are just beginning to emerge. Models vary widely when predicting the current pool of permafrost carbon, which is the fuel for future carbon emissions in a warmer world. The model average size of the permafrost carbon pool was estimated at 771 ± 100 Pg C (mean ± SE), about half as much as the measurement-based estimate (Schuur et al., 2015). The difference in the two estimates potentially is related, in part, to the fact that most models represented carbon to a depth of only 3 m. A smaller modeled carbon pool, in principle, could constrain forecasted carbon emissions. Normalizing the emissions estimates from the dynamic models by their initial permafrost carbon pool size, 15 ± 3% (mean ± SE) of the initial pool is expected to be lost as GHG emissions by 2100 (Schaefer et al., 2014). However, within these complex models, sensitivity to modeled Arctic climate change and the responses of soil temperature, moisture, and carbon dynamics are important controls over emissions predictions, not just pool size alone (Koven et al., 2013; Lawrence et al., 2012; Slater and Lawrence 2013).

These dynamic models also simultaneously assess the countering influence of plant carbon uptake that may partially offset permafrost carbon release. Warmer temperatures, longer growing seasons, elevated CO_2, and increased nutrients released from decomposing organic carbon all may stimulate plant growth (Shaver et al., 2000). New carbon can be stored in larger plant biomass or deposited into surface soils (Sistla et al., 2013). An intercomparison

of biogeochemical models applied to the permafrost region indicates much larger plant production responses to climate change in the last few decades than observation-based trends in plant productivity (McGuire et al., 2016), suggesting that future plant production responses to changing climate may also be less than models predict. A previous generation of ESMs that did not include permafrost carbon mechanisms but did simulate changes in plant carbon uptake estimated that the vegetation carbon pool could increase by 17 ± 8 Pg C by 2100, with increased plant growth also contributing to new soil carbon accumulation of similar magnitude (Qian et al., 2010). The models reviewed here with permafrost carbon mechanisms also include many of the same mechanisms that stimulate plant growth as the previous generation of models and generally indicate that increased plant carbon uptake will more than offset soil carbon emissions from the permafrost region for several decades as the climate becomes warmer (Koven et al., 2011; MacDougall et al., 2012; Schaefer et al., 2011). Over longer timescales and with continued warming, however, microbial release of carbon overwhelms the capacity for plant carbon uptake, leading to net carbon emissions from permafrost ecosystems to the atmosphere. Modeled carbon emissions projected under various warming scenarios translate into a range of 0.13 to 0.27°C additional global warming by 2100 and up to 0.42°C by 2300, but currently remain one of the least constrained biospheric feedbacks to climate (IPCC 2013).

In many of the model projections previously discussed, CH_4 release is not explicitly represented because fluxes are small. However, the higher GWP of CH_4 makes these emissions relatively more important than on a mass basis alone. Observed short-term temperature sensitivity of CH_4 from the Arctic possibly will have little impact on the global atmospheric CH_4 budget in the long term if future trajectories evolve with the same temperature sensitivity (Sweeney et al., 2016). Global models that include the short-term sensitivities of CH_4 to warming show increased CH_4 emissions with future warming in the northern permafrost region (Gao et al., 2013; Riley et al., 2011). Yet, these models conclude that if these increased emissions were to occur, they would have little influence on the climate system because of their relatively small magnitude. However, most models do not include abrupt thaw processes (i.e., thawing of ice-rich permafrost) that can result in lake expansion, wetland formation, and massive erosion and exposure to decomposition of previously frozen carbon-rich permafrost. A substantial area of the northern permafrost region is susceptible to abrupt thaw (Olefeldt et al., 2016), which could result in more substantial CH_4 emissions in the future than are currently projected by models. Although the current generation of comprehensive ESMs largely do not include abrupt thaw processes, progress is being made to include surface subsidence that occurs as a result of ground ice loss (Lee et al., 2014). A recent study suggests that the largest CH_4 emission rates will occur around the middle of this century when simulated thermokarst lake extent is at its maximum and when abrupt thaw under thermokarst lakes is taken into account (Schneider von Deimling et al., 2015). Furthermore, the simulated CH_4 fluxes can cause up to 40% of total permafrost-affected radiative forcing in this century. Similarly, no global models currently consider the effects of warming on CH_4 emissions from coastal systems in the Arctic. Models clearly need to include an expanded suite of processes, such as those described previously, that can affect CH_4 dynamics (Xu et al., 2016). These more comprehensive CH_4 models must be effectively benchmarked in a retrospective context (McGuire et al., 2016) before the research community can reduce uncertainty over changes in CH_4 dynamics of the northern permafrost region in response to future warming.

Laboratory-Based Empirical Upscaling

In addition to the amount of carbon stored in permafrost, the decomposability of organic matter determines how much carbon is released to the atmosphere. A recent synthesis using permafrost soil from various circumpolar locations assessed the decomposability of permafrost carbon using long-term (longer than 1 year) aerobic incubation

studies (Schädel et al., 2014). A small fraction of organic matter in thawed permafrost can decompose in weeks to months (Bracho et al., 2016; Dutta et al., 2006; Knoblauch et al., 2013; Lee et al., 2012), but the larger fraction decomposes over decades and even centuries (Schädel et al., 2014). Decade-long potential carbon release as CO_2 was estimated to range from 1% to 76% across a variety of soil types with strong landscape-scale variation. This landscape variation in decomposability was linked to the carbon-to-nitrogen ratio of the bulk organic matter, with higher ratio soils having a greater potential to release carbon during laboratory incubation. The carbon-to-nitrogen ratio is initiated by 1) the type of vegetation carbon that is input to the permafrost soil pool over years, centuries, and even longer; 2) subsequent microbial activity acting on those inputs; and 3) pedogenic processes that help control soil organic matter formation and decay. Upscaling these incubation results using a data-driven modeling approach estimated that soil carbon releases by 2100 (for RCP8.5) will be 57 PgC (Koven et al., 2015).

In a future climate, microbial decomposition of organic matter will happen under a wide variety of environmental conditions that control the amount and form of GHG release. Although temperature control over decomposition is implicit when considering permafrost thaw, northern high latitudes also are characterized by widespread lakes, wetlands, and waterlogged soils. Oxygen-rich conditions are found in drier upland soils where microbial decomposition produces mainly CO_2; oxygen-poor conditions occur in lowlands when ice-rich permafrost thaws, runoff is prevented by the underlying permafrost, and both CO_2 and CH_4 are produced by microbial decomposition. A recent meta-analysis compared GHG release from aerobic and anaerobic laboratory incubation conditions (Schädel et al., 2016). The study quantified that drier, aerobic soil conditions result in three times higher carbon release into the atmosphere compared to the same soil decomposing in wetter, anaerobic soil conditions. Most of the carbon released to the atmosphere was in the form of CO_2. Under anaerobic conditions, a small amount of carbon also was released as CH_4 (about 5% of total carbon release). Even though CH_4 is the more potent GHG, the much faster decomposition under aerobic conditions dominates the overall carbon release from permafrost. These results show that CO_2 released from drier and oxygen-rich environments will be as or more important than CO_2 and CH_4 released from oxygen-poor environments on a per-unit soil carbon basis. The ultimate effect of these ecosystem types on climate would be scaled, of course, by the landscape coverage of these drier and wetter environments. In addition, these results present laboratory potentials for GHG release from permafrost; there are variety of factors excluded from this technique, such as increased plant biomass input to the soils, changing plant communities, and the priming of old carbon decomposition from new plant litter inputs.

11.5 Societal Drivers, Impacts, and Carbon Management

Forestry is the most widespread human management activity that affects the carbon cycle in the most productive and accessible portion of the boreal forest. This section focuses on a case study of how wildfire management in Alaska has the potential to affect the fire cycle and, consequently, carbon pools via pathways described earlier in the chapter. In Alaska, all lands are classified into fire management planning options depending on the proximity to and density of human infrastructure. The range of management options include "Limited" (i.e., the least amount of management where fire activity is largely observed but not suppressed), "Modified," "Full," and "Critical" (i.e., assigned to lands immediately surrounding human settlements and key infrastructure and resources). Each option represents an increasing amount of human intervention to suppress wildfire activity. This case study describes a modeling experiment conducted to determine the impact of changing fire management planning options from the current designation of Limited or Modified to Full protection for all military lands in the greater Fairbanks, Alaska, area. This change

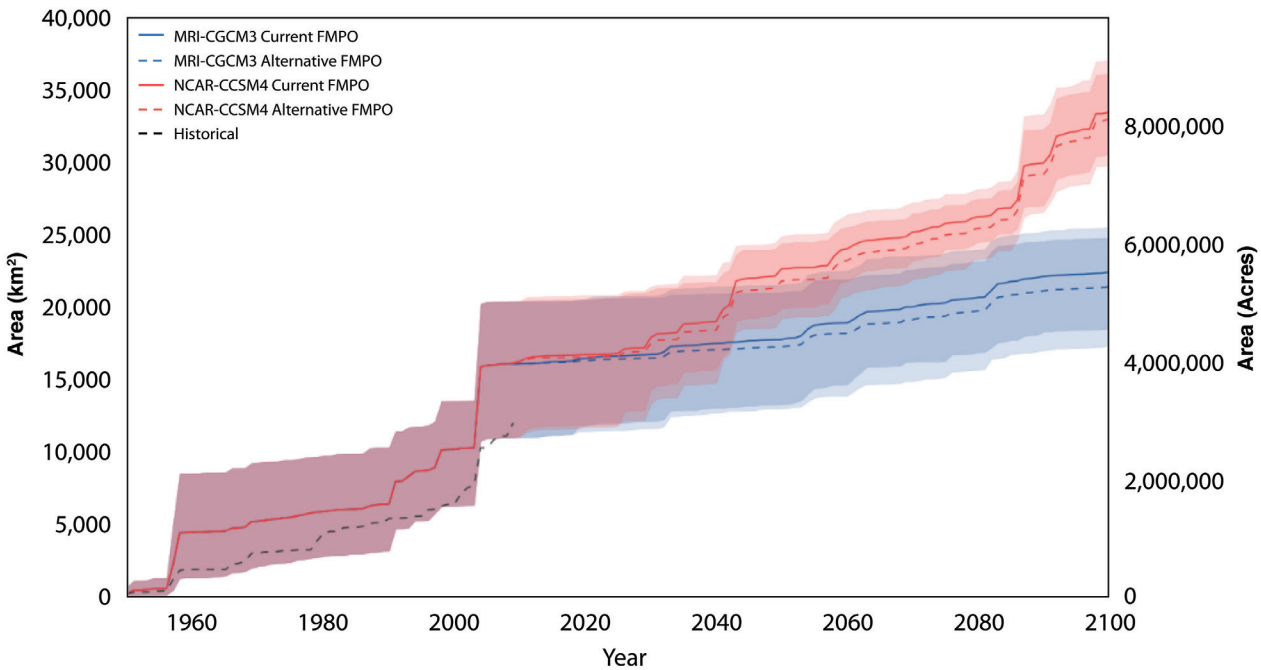

Figure 11.8. Effects of Two Climate Scenarios and Two Management Scenarios for a Subregion of Alaska. Cumulative area burned is modeled for the historical (1950 to 2009) and projected (2010 to 2100) periods for the Upper Tanana Hydrological Basin in interior Alaska near Fairbanks. Model results are presented for scenarios of fire management plan options (FMPO) driven by two Earth System Models: Meteorological Research Institute Coupled Global Climate Model version 3 (MRI-CGCM3) and National Center for Atmospheric Research Community Climate System Model version 4 (NCAR-CCSM4) using the Representative Concentration Pathway (RCP) 8.5 "business-as-usual" emissions scenario. Data presented are means, and shading indicates results from 200 model replicates; black dashed line is the actual fire record through 2010. [Figure source: Redrawn from Breen et al., 2016; Schuur et al., 2016, used with permission.]

in fire management led to a small increase in the projected number of fires per decade because more flammable vegetation (e.g., late successional conifer forests) would be preserved, but, importantly, there was a projected decrease in the cumulative area burned through 2100 compared to the status quo (see Figure 11.8, this page). Depending on the particular climate projection, active fire management (Full) decreased the projected cumulative area burned by 1.5% to 4.4% by 2100 (Breen et al., 2016). Differences in projected climate by 2100 arising from different climate model formulations have a strong impact on cumulative area burned, but fire management does have a small effect no matter the actual climate realized at the end of the century. In the absence of changing fire severity, the effect on carbon emissions would be exactly proportional to the difference in area burned. However, the somewhat small difference in cumulative area burned, and the proportional resulting effect on the carbon cycle, would need to be considered in context with the additional resources required to change the fire management planning option from the lower to higher level.

11.6 Summary and Outlook

Observation and modeling results synthesized in this chapter suggest that significant changes in the carbon stocks of Arctic and boreal regions may occur with impacts on the atmospheric GHG

budget. These projections primarily are due to the large pools of soil carbon preserved in cold and waterlogged environments vulnerable to a changing climate. This region, which previously has sequestered large amounts of carbon for centuries to millennia, is expected to transform into a one that acts as a net carbon source to the atmosphere over the next decades to centuries in a warming climate. Indeed, Arctic and boreal systems possibly have gone through this transition already.

Carbon offsets by vegetation remain a key part of the net response of this region to warming. Rising Arctic temperatures appear to have increased plant biomass, an effect observed in the tundra over the last three decades using satellite remote-sensing tools (Frost and Epstein 2014; Jia et al., 2003; Ju and Masek 2016) and field observations (Elmendorf et al., 2012; Salmon et al., 2016). A greener Arctic has important implications for regional and global climate because of anticipated increases in atmospheric CO_2 uptake, changes in surface energy, and altered nutrient and water cycling. Despite this long-term trend toward a greener Arctic, a distinct reversal of this trend has been observed for tundra from 2011 to 2014 (Epstein et al., 2015; Phoenix and Bjerke 2016), and the long-term trend is in contrast to boreal regions that show decreased NDVI (browning; Beck and Goetz 2011). Models, in contrast, tend to show consistent increases in plant growth, both in retrospective analyses (McGuire et al., 2016) and in future forecasts. Documenting changes in biomass with repeat LIDAR measurements is an approach for producing future datasets that help validate or refute model projections of enhanced carbon uptake.

Emerging research on disturbance of permafrost soils by abrupt thaw is another knowledge gap where new information on modeling and landscape mapping is helping to describe patterns and processes (Olefeldt et al., 2016). Abrupt permafrost thaw can trigger destabilization of permafrost and soils at rates much higher than predicted from changes in temperature alone. However, this disturbance occurs at specific points covering only a fraction of the landscape compared to that affected by the influence of temperature increases occurring regionally (Kokelj et al., 2017). New research is critical for highlighting the importance of this subgrid pulse disturbance at the landscape scale and for providing the process-level detail needed but currently lacking in regional- and global-scale models.

Lastly, apparent offsets in carbon flux estimates made by top-down atmospheric measurements and from bottom-up scaling of ecosystem measurements always will be hampered in this region because of the relative scarcity of study locations. New research and satellite capabilities currently focused on high-latitude ecosystems are helping to increase data coverage in this remote and understudied region and will set important baselines against which to measure future change.

SUPPORTING EVIDENCE

KEY FINDING 1

Factors that control terrestrial carbon storage are changing. Surface air temperature change is amplified in high-latitude regions, as seen in the Arctic where temperature rise is about 2.5 times faster than that for the whole Earth. Permafrost temperatures have been increasing over the last 40 years. Disturbance by fire (particularly fire frequency and extreme fire years) is higher now than in the middle of the last century (*very high confidence*).

Description of evidence base

Key Finding 1 is supported by observational evidence from ground-based and remote-sensing measurements. Documented changes in surface air temperatures (data.giss.nasa.gov/gistemp/maps) at a rate higher than the global average are consistent with model projections (Overland et al., 2014) and theory (Pithan and Mauritsen 2014). Permafrost temperatures documented in borehole networks (Biskaborn et al., 2015) are increasing, with the largest absolute temperature increases in cold permafrost regions (Noetzli et al., 2016; Romanovsky et al., 2016). Decadal trends (Flannigan et al., 2009; Kasischke and Turetsky 2006) and paleoecological reconstructions (Kelly et al., 2013) show that area burned, fire frequency, and extreme fire years are higher now than in the first half of the last century and likely will last even longer.

Major uncertainties

Data are not collected uniformly across regions and often are limited by site access. High-latitude observation stations are limited as well. Boreholes often are not located at sites where abrupt permafrost change is evident (Biskaborn et al., 2015). Area burned and other metrics of fire severity can be quantified by remote sensing, but some metrics rely on more limited ground-truth information. Direct measurements of permafrost temperature and fire extend back only 50 to 60 years, but these factors can respond to drivers (e.g., past temperature fluctuations and fire cycles) over even longer time intervals.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is high confidence that drivers of carbon pool change are increasing in strength. In addition, there is very high confidence that surface air temperature change is amplified in high-latitude regions, as seen in the Arctic, where temperature rise is about 2.5 times faster than that for the entire planet. There is high confidence that permafrost temperatures have been rising and that fire disturbance is increasing, although the data records for the latter are shorter compared to temperature records.

Summary sentence or paragraph that integrates the above information

For Key Finding 1, there is very high confidence that drivers of carbon pool changes are increasing in strength. Key Finding 1 is supported by a large amount of observational evidence documented in the peer-reviewed literature. Similar statements previously have been made in assessments of Arctic climate change, including IPCC (2013) and Melillo et al. (2014). Key uncertainties are the length of the data records and the limited ground-based information for variables such as fire severity.

KEY FINDING 2

Soils in the northern circumpolar permafrost zone store 1,460 to 1,600 petagrams of organic carbon (Pg C), almost twice the amount contained in the atmosphere and about an order of magnitude more carbon than contained in plant biomass (55 Pg C), woody debris (16 Pg C), and litter (29 Pg C) in the boreal and tundra biomes combined. This large permafrost zone soil carbon pool has accumulated over hundreds to thousands of years. There are additional reservoirs in subsea permafrost and regions of deep sediments that are not added to this estimate because of data scarcity (*very high confidence*).

Description of evidence base

Key Finding 2 is supported by observational evidence from ground-based measurements of ecosystem carbon pools. Large surface soil carbon pools (to 1 m in depth) have been reported in the literature for decades (e.g., Gorham 1991), with new information on deeper permafrost carbon pools accumulating over the last decade (Hugelius et al., 2014; Schuur et al., 2015; Tarnocai et al., 2009; Zimov et al., 2006). Biomass pools have been synthesized from forest inventory data (Pan et al., 2011), and more recently using remote sensing (Neigh et al., 2013; Raynolds et al., 2012).

Major uncertainties

Soils data are not collected uniformly across regions and often are limited by site access (Johnson et al., 2011). Deep-soil inventories (>1 m in depth) are much more limited than surface soil information (Hugelius et al., 2014). Biomass inventories often exclude unmanaged forests, which are prevalent in this region (Pan et al., 2011). Aboveground plant biomass is best quantified, whereas root biomass most often is estimated (Saugier et al., 2001). Coarse wood and litter also are poorly known carbon pools, and, in some cases, large-scale estimates for these pools are model derived.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is very high confidence that permafrost soil carbon stocks are large and protected currently by waterlogged and frozen soil conditions across much of the region. There is also very high confidence that soil carbon stocks are more than 10 times larger than stocks of carbon in plant biomass, woody debris, and litter pools.

Summary sentence or paragraph that integrates the above information

In Key Finding 2, there is very high confidence that permafrost soil carbon stocks are large and protected currently by waterlogged and frozen soil conditions across much of the region. There is also very high confidence that soil carbon stocks are more than 10 times larger than stocks of carbon in plant biomass, woody debris, and litter pools. This Key Finding is supported by a large amount of observational evidence documented in the peer-reviewed literature. The key uncertainty is the scarcity of measurements for deep permafrost soil carbon relative to those for surface soils, biomass inventories in unmanaged forests, and belowground biomass.

KEY FINDING 3

Following the current trajectory of global and Arctic warming, 5% to 15% of the soil organic carbon stored in the northern circumpolar permafrost zone (mean 10% value equal to 146 to 160 Pg C) is considered vulnerable to release to the atmosphere by the year 2100. The potential carbon loss is likely to be up to an order of magnitude larger than the potential increase in carbon stored in plant biomass regionally under the same changing conditions (*high confidence, very likely*).

Description of evidence base

Key Finding 3 is supported by observational and modeling evidence from a range of literature sources and synthesized by Schuur et al. (2015). Observational data include soil incubation studies (Schädel et al., 2014, 2016) and synthesis of field observations (Belshe et al., 2013). Modeling evidence includes Burke et al. (2012), Burke et al. (2013), Koven et al. (2011), MacDougall et al. (2012), Schaefer et al. (2011), Schaphoff et al. (2013), Schneider von Deimling et al. (2012), and Zhuang et al. (2006).

Major uncertainties

This estimate is based largely on estimates of top-down permafrost thaw as a result of a warming climate and does not include abrupt permafrost thaw processes that can expose permafrost soils to higher temperature more rapidly than predicted by top-down thaw alone. Increasing evidence suggests that abrupt thaw processes are likely to be widespread across Arctic and boreal regions (Olefeldt et al., 2016). Waterlogging (oxygen limitation) is common in surface and subsurface soils because of limited infiltration as a result of permafrost. Oxygen limitation slows the decomposition of organic matter, but both wetter or drier soil conditions can result from degrading permafrost at the site scale. Whether high-latitude terrestrial ecosystems will be wetter or drier in the future at the landscape scale is unclear.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is high confidence that permafrost soil carbon stocks are vulnerable to loss with changing climate conditions. This is also true of changing plant biomass but with more uncertainty about the relative magnitude of change.

Estimated likelihood of impact or consequence, including short description of basis of estimate

Thawing permafrost has significant impacts on the global carbon cycle, serving as a source of carbon dioxide (CO_2) and methane (CH_4) emissions. The level of emissions projected here very likely will accelerate the rate of global climate change. Future emissions from the permafrost zone are expected to be a fraction of those from fossil fuels, but they may be similar to current estimates of land-use change emissions.

Summary sentence or paragraph that integrates the above information

For Key Finding 3, there is high confidence that permafrost soil carbon stocks are vulnerable to loss with changing climate conditions. Thawing permafrost has a significant impact on the global carbon cycle, serving as a source of CO_2 and CH_4 emissions. Permafrost-zone emissions levels are expected to be a fraction of those from fossil fuels, but they may be similar to current estimates of land-use change emissions. Key Finding 3 is supported by observational and modeling evidence documented in the peer-reviewed literature. Primary key uncertainties include the influence of abrupt thaw processes that can expose permafrost soil carbon much more rapidly than top-down thawing, which is the process represented by model projections. Also unclear is the degree to which soil waterlogging will increase or decrease as permafrost degrades, which influences the relative release of CO_2 and CH_4.

KEY FINDING 4

Some Earth System Models project that high-latitude carbon releases will be offset largely by increased plant uptake. However, these findings are not always supported by empirical measurements or other assessments, suggesting that structural features of many models are still limited in representing Arctic and boreal zone processes (*very high confidence, very likely*).

Description of evidence base

Key Finding 4 is supported by observational and modeling evidence from a range of literature sources. Modeling results are based on a permafrost carbon model intercomparison project that summarizes the results for 1960 to 2009 for 15 Earth System Models (McGuire et al., 2016) and on an earlier model intercomparison of dynamic global vegetation models for high latitudes (Qian et al., 2010). Observational data include tundra and boreal normalized difference vegetation index (NDVI) trend studies (Beck and Goetz 2011; Epstein et al., 2015) and expert assessment (Abbott et al., 2016).

Major uncertainties

NDVI trends represent changes in canopy and thus are not directly measuring carbon pools; observational datasets at regional to continental scales in the Arctic are scarce, making model evaluation difficult.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is high confidence that model projections are not always in agreement with observational constraints about plant carbon uptake offset.

Estimated likelihood of impact or consequence, including short description of basis of estimate

Thawing permafrost has significant impacts to the global carbon cycle, serving as a source of CO_2 and CH_4 emissions. Plant uptake may offset some of these releases, but the mismatch between models and observations may cause significant over- or underestimates of this offset, as well as shift the timing of significant net carbon change for this region.

Summary sentence or paragraph that integrates the above information

For Key Finding 4, there is high confidence that model projections are not always in agreement with observational constraints about plant carbon uptake offset. Thawing permafrost has significant impacts to the global carbon cycle, serving as a source of CO_2 and CH_4 emissions. Plant uptake may offset some of that release, but the mismatch between models and observations may cause significant over- or underestimates of this offset, as well as shift the timing of significant net carbon change for this region. Key Finding 4 is supported by observational and modeling evidence documented in the peer-reviewed literature. Primary key uncertainties include the response of plant growth to multiple global change factors, including primarily CO_2 fertilization but also rising temperatures, changes in precipitation and growing season length, and changes in species distribution. Other uncertainties include deposition and storage of new carbon into surface soils.

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12 Soils

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KEY FINDINGS

1. Estimates for soil carbon stocks in the conterminous United States plus Alaska range from 142 to 154 petagrams of carbon (Pg C) to 1 m in depth. Estimates for Canada average about 262 Pg C, but sampling is less extensive. Soil carbon for Mexico is calculated as 18 Pg C (1 m in depth), but there is some uncertainty in this value (*medium confidence*).

2. Most Earth System Models (ESMs) are highly variable in projecting the direction and magnitude of soil carbon change under future scenarios. Predictions of global soil carbon change through this century range from a loss of 72 Pg C to a gain of 253 Pg C with a multimodel mean gain of 65 Pg C. ESMs projecting large gains do so largely by projecting increases in high-latitude soil organic carbon (SOC) that are inconsistent with empirical studies that indicate significant losses of soil carbon with predicted climate change (*high confidence*).

3. Soil carbon stocks are sensitive to agricultural and forestry practices and loss of carbon-rich soils such as wetlands. Soils in North America have lost, on average, 20% to 75% of their original top soil carbon (0 to 30 cm) with historical conversion to agriculture, with a mean estimate for Canada of 24% ± 6%. Current agricultural management practices can increase soil organic matter in many systems through reduced summer fallow, cover cropping, effective fertilization to increase plant production, and reduced tillage. Forest soil carbon loss with harvest is small under standard management practices and mostly reversible at the century scale. Afforestation of land in agriculture, industry, or wild grasslands in the United States and Canadian border provinces could increase SOC by 21% ± 9% (*high confidence*).

4. Large uncertainties remain regarding soil carbon budgets, particularly the impact of lateral movement and transport of carbon (via erosion and management) across the landscape and into waterways. By 2015, cumulative regeneration of soil carbon at eroded agricultural sites and the preservation of buried, eroded soil carbon may have represented an offset of 37 ± 10% of carbon returned to the atmosphere by human-caused land-use change (*medium confidence*).

5. Evidence is strong for direct effects of increased temperature on loss of soil carbon, but warming and atmospheric carbon dioxide increases also may enhance plant production in many ecosystems, resulting in greater carbon inputs to soil. Globally, projected warming could cause the release of 55 ± 50 Pg C over the next 35 years from a soil pool of 1,400 ± 150 Pg C. In particular, an estimated 5% to 15% of the peatland carbon pool could become a significant carbon flux to the atmosphere under future anthropogenic disturbances (e.g., harvest, development, and peatland drainage) and change in disturbance regimes (e.g., wildfires and permafrost thaw) (*medium confidence*).

Note: Confidence levels are provided as appropriate for quantitative, but not qualitative, Key Findings and statements.

12.1 Introduction

Globally, soils contain more than three times as much carbon as the atmosphere and four and a half times more carbon than the world's biota (Lal 2004); therefore, even small changes in soil carbon stocks could lead to large changes in the atmospheric concentration of carbon dioxide (CO_2). Despite their importance, however, stocks of soil organic carbon (SOC), which is the carbon component of soil organic matter (SOM), have been depleted through changes in land use and land cover and unsustainable land management practices associated with agriculture, grazing, and forest management. To better manage and sustain SOC stocks, a focused understanding of microbial and biogeochemical processes that interact in soils, regardless of land cover, to control soil carbon stabilization and destabilization is needed. Soil organic matter (the organic component of soil, consisting of organic residues at various stages of decomposition, soil organisms, and substances synthesized by soil organisms) also is considered a central indicator of

soil health because it regulates multiple ecosystem services that humanity derives from soils, including moderation of climate. SOM stores nutrients, increases water-holding capacity to promote plant growth, limits leaching of nutrients, and adds structure that improves drainage and reduces erosion (Oldfield et al., 2015).

The current best estimates for global SOC stocks are 1,400 ± 150 petagrams of carbon (Pg C) to 1 m in depth and 2,060 ± 220 Pg C to 2 m in depth (Batjes 2016). These values are derived from the Harmonized World Soil Database with corrections for underrepresented regions, including the Northern Circumpolar Region, using measured soil profiles and geospatial modeling. The resulting values are consistent with other global SOC pool estimates (Govers et al., 2013; Köchy et al., 2015). An estimated 90 to 100 Pg C is released by soils to the atmosphere as soil respiration each year, an efflux that represents both heterotrophic (approximately 51 Pg C) and autotrophic (approximately 40 Pg C) respiration (Bond-Lamberty and Thomson 2010; Hashimoto et al., 2015), roughly balanced by carbon incorporated into SOC from plant residues. This flux value can be compared to estimates from the most recent Intergovernmental Panel on Climate Change (IPCC) report that estimated the gross efflux from surface ocean water to the atmosphere as 78.4 Pg C per year (with a net sink of 2.3 ± 0.7 Pg C per year), carbon emissions from fossil fuel combustion and cement production as 7.8 ± 0.6 Pg C per year, and outgassing from freshwater as 1.0 Pg C per year (Ciais et al., 2013). Soil carbon storage and flux at a given location are controlled by variations in 1) soil-forming factors (Jenny 1941; McBratney et al., 2003; Mishra et al., 2010), 2) anthropogenic activities (Lal 2004), and 3) climatic forcings (Heimann and Reichstein 2008; Richter and Houghton 2011). Future change in the frequency of climatic extremes (Seneviratne et al., 2012) and land use and land management (Nave et al., 2013; Ogle et al., 2010; Wills et al., 2014) may alter SOC stocks and fluxes that affect land feedbacks to climate change, changing the magnitude of, or even reversing (i.e., change from sink to source), the land carbon sink (Friedlingstein et al., 2014).

Soils of North America store 366 to 509 Pg of organic carbon to 1 m in depth based on continental-scale analyses (Batjes 2016; Liu et al., 2013). Breakdown of SOC stocks by country are discussed in more detail later in this chapter. At the continental scale, nearly 75% of SOC stocks down to 1 m are found in the top 30 cm (Liu et al., 2013), which also is the portion of the soil profile most vulnerable to changes induced by land-use and land-cover changes, disturbance and extreme events, management practices, and climate change. Several knowledge gaps exist in the current ability to measure SOC stocks and fluxes across North America. Researchers employ diverse analytical methods to measure carbon concentration and take measurements at different depths; furthermore, many measurements lack bulk density estimates that are needed to calculate stock estimates. Most SOC stock estimates lack systematic uncertainty (i.e., error propagation) estimates. Consequently, this chapter shows many values of stocks and fluxes without companion uncertainty values. Therefore, significant risks exist for biased conclusions due to inadequate and uneven distributions of SOC profile observations, especially in permafrost regions (Mishra et al., 2013), for depths >1 m and in bulk density estimates for organic soils (Köchy et al., 2015). Recent updates to soil databases have improved coverage, but distributions of available samples across geographic regions are uneven and thus not sufficient to fully characterize SOC dependence on climate, edaphic factors, and land-cover types (Hengl et al., 2014; Mishra and Riley 2012). However, recent efforts, notably the U.S. Department of Agriculture's (USDA) Rapid Carbon Assessment (RaCA), will yield a much more consistent estimate of current soil carbon stocks (see Section 12.4.1, p. 479). Similarly, RaCA recently initiated a field-based soil carbon inventory for Mexico, and comprehensive stock estimates for different regions and land uses are forthcoming (see Section 12.4.2, p. 481).

Since cultivation of land began nearly 12,000 years ago, humans have been altering soil carbon stocks. Just since 1850, human degradation of soil worldwide may have resulted in a loss of 44 to 537 Pg SOC, largely through land-use change and conversion to agriculture (Lal 2001; Paustian et al., 1997). Globally, agricultural soils have lost 20% to 75%, or 30 to 40 megagrams of carbon (Mg C) per hectare (ha), of their antecedent SOC pool (Lal et al., 2015). In contrast, afforestation (the establishment of forest cover on land that previously did not have tree cover) and land restoration have the potential to recover depleted SOC stocks from the atmosphere (Lal 2004). For example, newly afforested lands cover 4 billion ha globally and have a carbon sequestration potential of 1.2 to 1.4 Mg C per year (Lal et al., 2015). Meta-analysis of afforestation effects on soil carbon storage in the United States and Canadian border provinces found that land conversion to forest from agriculture, industry, or wild grassland increased SOC by 21% ± 9% (Nave et al., 2013). The researchers found that the largest increase was in lands previously used for industrial purposes such as mining (173%), for areas with woody encroachment into unmanaged grassland (31%; see Ch. 10: Grasslands, p. 399), and for agricultural areas in the Northern Plains (32%; see Ch. 5: Agriculture, p. 229). Such SOC increases via afforestation and reforestation contribute to the net carbon sequestration by U.S. forests, currently estimated at 313 ± 40 teragrams of carbon (Tg C) per year (Lu et al., 2015).

12.2 Carbon Cycling Processes in Soils

Progress has been made over the last 10 years in understanding specific processes that determine the magnitude and direction of SOC stabilization and destabilization (see Figure 12.1, p. 473). This new information will not only help explain spatial patterns of SOC in North America, but also will help improve modeling of the large soil carbon pool in Earth System Models (ESMs). Outlined here are the processes that govern overall carbon stocks and fluxes through soils, from inputs through microbial transformations in the bulk soil and rhizosphere, and the protection mechanisms that govern the overall longevity of carbon in soils.

12.2.1 Precipitation

Overriding many soil carbon processes is the complicated role of precipitation and moisture on soil carbon stocks. Precipitation effects on SOC are complicated by the various and often opposing effects of precipitation on the various processes that control carbon stabilization and destabilization. On one hand, where moisture is limiting, increased soil moisture stimulates soil microbial activity, thus increasing soil respiration and destabilization of soil carbon. On the other hand, precipitation has strong effects on both vegetation type and plant production, and thus increases in precipitation in moisture-limited systems generally lead to increases in soil carbon through indirect effects on enhanced plant production, particularly increased root production (Jobbágy and Jackson 2000). In a global analysis (Jobbágy and Jackson 2000) total soil carbon content increased with precipitation and clay content and decreased with temperature. These results match numerous regional studies showing that precipitation in temperate ecosystems has a strong and positive relationship with SOC, likely through effects on total plant biomass, especially belowground biomass (Burke et al., 1989; Liu et al., 2012). Taken together these results suggest a greater response of plant production compared to decomposition from increased precipitation.

Several analyses have noted a wide divergence in estimates of soil carbon stocks from terrestrial biosphere models (Tian et al., 2015; Todd-Brown et al., 2013). Todd-Brown et al. (2013) noted that the parameterization of soil heterotrophic respiration was a significant cause of the discrepancy in model predictions, while Tian et al. (2015) suggested that mechanisms such as changes in the proportion of labile to passive soil carbon pools, as well as sensitivities of respiration to climate, are significant sources of uncertainty in the modeling estimates of soil carbon. Thus, more accurate biome-specific analyses of the effects of precipitation on soil respiration,

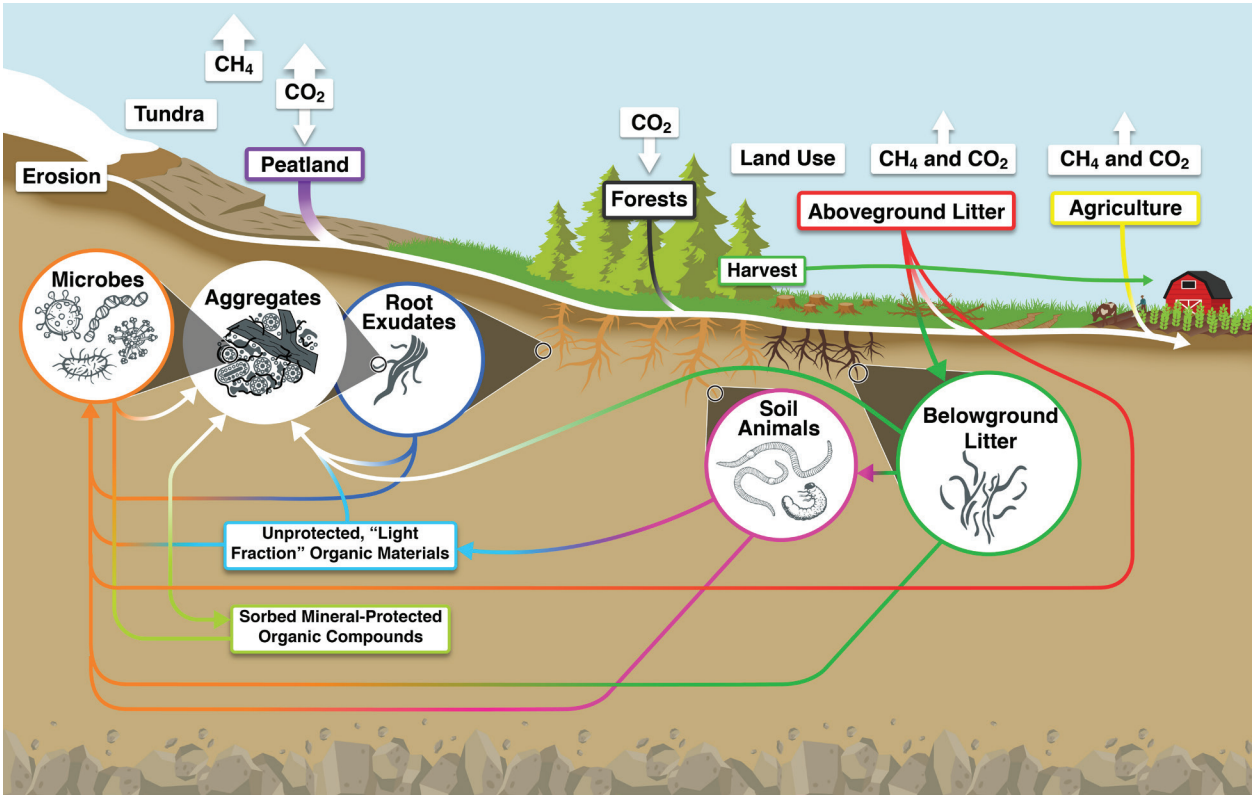

Figure 12.1. Processes Involved in Controlling Fluxes and Stabilization of Soil Carbon. A variety of soil animals and microbes can process plant litter that contributes to a pool of unprotected particulate organic matter (OM) with a relatively short turnover time. Alternatively, soil microbes also can process this litter into more stabilized forms such as aggregates or mineral-protected OM with relatively long turnover times. In this carbon pool, belowground litter appears to be preferentially stabilized, partly because of its proximity to both microbes and minerals. Root exudates may contribute to microbial carbon pools or to priming (i.e., the loss of mineral-protected soil carbon). Respiratory losses—occurring at all stages of biotic processing—can be affected by microbial carbon use efficiency and by conditions in the natural environment or those arising from land use. Not only can land use significantly affect both the quality and quantity of plant residues delivered to soils and their processing, it also can affect erosional losses and deposition. Climate change, especially in northern latitudes, may cause significant losses of soil carbon. (Key: CO_2, carbon dioxide; CH_4, methane.)

litter and root production, and vegetation type will be needed to improve soil carbon models.

12.2.2 Plant Litter Inputs

Many factors, including climate regime, atmospheric CO_2, land management, soil mineralogy and fertility, and nitrogen deposition strongly influence the structure of the plant community and thus the amount and quality of organic inputs (e.g., litter, wood, and root debris) to the surface of soils (Jandl et al., 2007; McLauchlan 2007; Smith et al., 2007). For example, elevated nitrogen deposition and high soil fertility generally increase plant shoot:root ratios and also decrease concentrations of plant protective compounds such as lignin (Haynes and Gower 1995; Luo and Polle 2009; Pitre et al., 2007). Chemical composition of litter, variably measured as carbon:nitrogen, lignin:nitrogen, or by the presence of complex aromatic compounds, has been shown to influence litter decomposition (Papa et al., 2013; Trofymow et al., 1995; Wardle et al., 2002), with high lignin or aromatic content observed to limit decomposition rates. However, the linkages among litter quantity, litter composition, and SOC stocks

are much less clear than would be expected due to other contributing factors. For example, several long-term litter manipulation experiments have shown that increased litter inputs do not always result in increased SOC storage (Lajtha et al., 2014a, 2014b; Mayzelle et al., 2014). Fresh carbon inputs can alter the decomposition of existing SOM because microbes, which play a major role as decomposers in soil ecosystems, will use the new inputs as fuel to decompose existing SOM (Bernal et al., 2016; Crow et al., 2009; Georgiou et al., 2015), resulting in a net decrease in SOC. Site-specific differences in soil mineralogy and microbial physiology also can influence the magnitude of response in SOC concentrations to changes in litter inputs (Geyer et al., 2016; see Section 12.2.3, this page). These kinds of interactions with soil minerals and microbes help to explain why chemical factors, such as lignin content, that are known to control litter decomposition do not always appear to be primary controls on SOC stabilization or destabilization (Rasse et al., 2006; Sulman et al., 2014). There also is evidence that root litter may be preferentially stabilized over shoot-derived litter (Iversen et al., 2008; Kong and Six 2010; Rasse et al., 2005; Russell et al., 2004). Thus, further research is needed to determine how changes in net primary production (NPP), vegetation, and litter quality due to rising atmospheric CO_2 concentrations will affect SOC stabilization in the future.

12.2.3 Soil Microbes

Soil microbes, including bacteria, fungi, and archaea, ultimately process all carbon inputs; consequently, microbes are referred to as "the eye of the needle through which all organic materials must pass" (Jenkinson 1977). The organic products and by-products of microbial decomposition, including microbial necromass, can accumulate in soils as SOM, and the chemistry of SOM is distinct from its source material including litter, roots, insect and animal necromass, and wood. The transformation from litter inputs through microbes and into SOM produces inorganic, carbon-containing gases such as CO_2 and methane (CH_4) through microbial respiration. Because of its important role in carbon transformation, the soil microbial community is key to understanding SOC stocks (Bernal et al., 2016; Guenet et al., 2012), even though the microbial biomass is typically only 1% to 2% of total SOM mass (Xu et al., 2013). Understanding microbial response to microclimate is key to understanding the carbon balance of soils under climate change, because soil balance under changing temperature and moisture is dependent on microbial community and physiological responses to changing temperature and moisture (e.g., Billings and Ballantyne 2013; Yan et al., 2016).

In addition to their direct role mineralizing SOM into inorganic gases, microbes contribute to physical mechanisms of SOC stabilization, indirectly affecting the rate and nature of SOC inputs from plants. A key mechanism of SOC stabilization is protection within soil aggregates (Six et al., 2002), and fungal mycelia and bacterial extracellular polysaccharides are important in forming and stabilizing these aggregates (Aspiras et al., 1971). SOC also is protected by chemical interactions with minerals, particularly silt and clay (Six et al., 2002), and microbes living on minerals may facilitate these interactions by depositing microbially derived carbon directly onto mineral surfaces (Uroz et al., 2015). Microbes can affect plant carbon inputs by regulating plant nutrient supply (Bever et al., 2010; van der Heijden et al., 2006), which affects plant community composition and the timing, mass, and properties of plant inputs of litter and exudates. Thus, although they compose a small fraction of SOC stocks, microbes play a central role in the SOC cycle, affecting inputs, storage, and outputs in diverse ways.

12.2.4 Macrofauna (Food Web)

Soil is home to millions of different organisms, from microorganisms to soil animals (fauna) such as microscopic roundworms (nematodes), tardigrades, rotifers, collembolans, mites, isopods, ants, spiders, and earthworms (Orgiazzi et al., 2015). These fauna exist in food webs containing multiple trophic levels—herbivores that feed directly on the roots of living plants, consumers that feed on living microorganisms associated with dead organic

materials, predators that prey on other soil fauna, and plant or animal parasites and pathogens (Coleman and Wall 2015). Through soil bioturbation and feeding on plant roots, organic matter, and their associated microorganisms, soil animals are intimately involved in every step of SOM turnover and soil formation. Sometimes referred to as "ecosystem engineers," soil animals play a disproportionate role in the carbon cycle relative to their abundance and biomass. Carbon stocks of the soil fauna range from 0.3 to 50 kilograms of carbon per hectare, with desert soils containing the smallest faunal biomass and temperate grassland and tropical rainforest soils the greatest (Fierer et al., 2009). However, across biomes, the biomass of soil fauna typically represents less than 3% of the total biomass of living soil organisms, with soil microorganisms making up the majority. Despite their low biomass relative to soil microbes, soil fauna contribute significantly to carbon cycling through their regulation of microbial activity and through their physical mixing of organic materials and soil. The presence of soil fauna stimulates decomposition, respiration rates (i.e., CO_2 flux), and losses of dissolved organic carbon through leaching (de Vries et al., 2013). The positive impact of soil fauna on carbon cycling is attributed to organic matter fragmentation, which increases 1) the surface area available for microbial colonization; 2) the partial digestion of organic materials, enhancing their decomposability; 3) the direct contact of soil microbes with organic matter; and 4) the direct consumption of soil microbes—all impacts which stimulate microbial activity and the release of carbon and nutrients (Coleman and Wall 2015). However, one study found that the activity of earthworms increases carbon stabilization onto minerals to a greater degree than the increase in carbon mineralization, leading to net soil carbon increase (Zhang et al., 2013). Current ecosystem-scale models and ESMs typically overlook the significant effects of soil fauna on the carbon cycle, but guidelines for development of next-generation models call for explicitly incorporating soil food web properties and the responses of soil fauna to land use and climate change (de Vries et al., 2013).

12.2.5 Rhizosphere Interactions

The rhizosphere is defined as an area of soil where microbial activity is stimulated by the presence of roots. A substantial portion of plant biomass is located below ground in the form of roots. Estimates of belowground NPP based on root:shoot ratios assign 30% to 60% of total plant biomass to roots, depending on the biome (Bolinder et al., 2007; Rytter 2001). Regularly shedding sloughed cells and mucilage, roots exude a variety of simple carbon compounds into the soil immediately surrounding them (Hirsch et al., 2013). These root "exudates" comprise primarily organic acids, sugars, and amino acids (Hirsch et al., 2013; Jones 1998). These exudates can interact with minerals by sorption or can liberate organic compounds and nutrients for plant or microbial uptake (Dessureault-Rompre et al., 2007; Keiluweit et al., 2015). In general, the mass of soil in the rhizosphere makes up a smaller fraction (<40%) of total soil than does root-free soil, but it disproportionately affects carbon cycling. For example, microbial biomass, extracellular enzyme activity, decomposition, and mineralization rates are consistently higher in rhizosphere soil compared with those in bulk soil. Fungal hyphae can extend >40 cm away from roots (Finlay and Read 1986), extending the influence of root carbon past the rhizosphere (Zak et al., 1993). Dead root biomass is a substrate source for saprotrophic microbes and detritivores, while living roots are a source of carbon to mycorrhizal fungi.

Mycorrhizal material, shown to be a dominant pathway through which carbon enters the SOM pool, exceeds the input via leaf litter and fine-root turnover (Godbold et al., 2006). Mycorrhizae also may stimulate the decomposition of soil carbon to mine nutrients, paradoxically causing destabilization of soil carbon pools. The effects of mycorrhizae on soil carbon balance are thus complicated by the balance between carbon stabilization effects and soil carbon priming effects (Brzostek et al., 2015). However, recent research (Averill and Hawkes 2016;

Averill et al., 2014) demonstrated that ecosystems dominated by plants with symbiotic ectomycorrhizal fungi store more carbon in soils than ecosystems dominated by arbuscular mycorrhizae–associated plants.

12.2.6 Nitrogen Effects on SOM Dynamics

There are substantial interactions between biogeochemical cycles of carbon and nitrogen. Human activities (e.g., fertilizer production, fossil fuel combustion, and industry) have substantially increased nitrogen supply to ecosystems (Vitousek et al., 1997). Global annual nitrogen deposition has increased tenfold over the past 150 years (Lamarque et al., 2005; Yue et al., 2016), although nitrogen deposition has decreased significantly across North America over the last decade due to pollution control. Historic nitrogen loading increased NPP (Elser et al., 2007; LeBauer and Treseder 2008; Xia and Wan 2008), which in turn increased carbon inputs to the forest floor and overall production of plant biomass (Hyvonen et al., 2007; Vitousek et al., 1997). Across biomes, total soil carbon tends to increase with experimental nitrogen addition (Yue et al., 2016), yet this may result less from increases in inputs and more from altering the extent or rates of decomposition (Frey et al., 2014; Liu and Greaver 2010). Microbial decomposition of soil carbon is generally retarded by nitrogen deposition (Hagedorn et al., 2003), but carbon allocation to roots also decreases with nitrogen deposition, limiting new carbon inputs to soil. However, a recent meta-analysis suggested that the reduction in soil carbon respiration, and thus increase in soil carbon stocks resulting from nitrogen deposition, might be equal in magnitude to the amount of additional carbon sequestered by aboveground vegetation (Janssens et al., 2010). Literature surveys suggest that the soil carbon response to anthropogenic nitrogen will fall in the range of 0 to 23 grams of carbon per gram of nitrogen added (Reay et al., 2008), but the uncertainty around this value is very high.

12.2.7 Protection Mechanisms

The extent of carbon protection (i.e., resistance to microbial decomposition) in soil historically has been attributed to litter chemistry, and this remains an element of carbon persistence (Clemente et al., 2011) in organic soils or organic soil horizons that accumulate on the surface of the mineral soil in forests. In recent decades, studies have shown that the controls on carbon stability in mineral soils are more likely dominated by physical and biological factors in the soil environment (Jastrow et al., 2006; Lehmann and Kleber 2015; Lin and Simpson 2016). Physical protection by spatial isolation (i.e., aggregate formation; McCarthy et al., 2008) and chemical associations with soil minerals (i.e., sorption) are both key drivers of carbon persistence in soils. Protection of carbon within soil aggregates (i.e., physical associations between soil minerals and organic compounds) can lead to long-term carbon storage in soils (Jastrow et al., 1996; Six et al., 2004). Compromising the physical structure of aggregates such as by tillage can result in substantial carbon losses because SOC becomes more available physically to decomposition (Navarro-Garcia et al., 2012). Alternatively, carbon may be protected via sorption to soil minerals in which reactive surfaces, including phyllosilicates, oxides, and other minerals, bind carbon molecules via chemical bridges and bonds. The types of compounds sorbed range from discrete chemical compounds (Solomon et al., 2012) to fragments of partially decayed microbial biomass (Courtier-Murias et al., 2013). Mineral-associated carbon stocks can have half-lives ranging from 30 to 4,500 years (Hall et al., 2015a, 2015b; Heckman et al., 2014), yet they can be rendered vulnerable as local environmental conditions change in ways that alter the chemical binding strength, such as changes in precipitation, infiltration, or temperature. In addition, larger-scale processes can serve to protect soil carbon, such as freezing, waterlogging, cryoturbation, or erosion deposition (Kaiser et al., 2007; Grosse et al., 2011; Berhe et al., 2007; Kroetsch et al., 2011).

12.2.8 Losses

Gas Fluxes

Gases including CO_2 and CH_4 are released from soils as a result of SOM and litter decomposition by soil microbes. Respiration of live roots and their

associated mycorrhizal symbionts also release CO_2 into the subsurface (Bond-Lamberty et al., 2004; Hanson et al., 2000; Subke et al., 2006; Tang et al., 2005). Globally, approximately 90 to 100 Pg C per year was released to the atmosphere from microbial soil respiration, and the projected rate increase is about 0.1 Pg C per year under a warming climate (Bond-Lamberty and Thomson 2010; Hashimoto et al., 2015). Soil respiration is affected by soil temperature, soil moisture, and organic carbon availability (Davidson and Janssens 2006). Typically, warming increases microbial respiration, while increases in moisture variably affect microbial respiration with maximum CO_2 emissions observed under partially saturated conditions. As soils saturate, methanogenesis is likely to emerge as the dominant carbon emission. Other global change factors such as elevated atmospheric CO_2 and naturally and anthropogenically altered soil nitrogen status also interactively affect soil respiration in direct and indirect ways (Billings and Ziegler 2008; Zhou et al., 2016). Also observed are vast differences in the amount of gas evolution as a function of landscape heterogeneity, underlying geology and soil type, and vegetative cover, as well as daily and seasonal temporal changes. Consequently, ESMs have not fully used soil respiration data for validation and calibration (Phillips et al., 2016).

Compared with CO_2, CH_4 has 28 times higher global warming potential over a 100-year time horizon (Saunois et al., 2016). Worldwide biogenic (i.e., associated with plants, animals, and microbes) sources of CH_4 emissions, including those from natural ecosystems, agriculture, biomass burning, and landfill waste, are estimated to be 0.33 Pg C per year or 12.4 Pg CO_2 equivalent1 (CO_2e) per year, including anthropogenic biogenic sources of 7.4 Pg CO_2e per year (Tian et al., 2016). The U.S. inventory of greenhouse gases (GHGs) estimated anthropogenic total CH_4 emissions of 0.87 Pg CO_2e per year in 2015 if the 100-year global warming potential of 28 is used to calculate the CO_2 equivalent for CH_4, including anthropogenic biogenic sources of 0.42 Pg CO_2e per year, mostly from agriculture, landfill, and waste management (U.S. EPA 2017). Methane in North American soils is produced primarily under anaerobic conditions by methanogenic microbes, mostly in freshwater wetlands and rice paddies. However, CH_4 emissions are the net balance of both CH_4 production and oxidation (i.e., CH_4 destruction) by methanotrophic microbes (Tate 2015). The oxidation (i.e., consumption) of CH_4 in wetlands is important and may reduce potential CH_4 emissions by over 50% (Segarra et al., 2015).

Erosion

Soil erosion mobilizes about 75 Pg of soil each year by water and wind, with most erosion stemming from agricultural lands (Berhe et al., 2007). This accelerated movement of soil has major effects on the carbon cycle, most obviously because erosion physically removes SOC from soil profiles, exposing some fraction to oxidation during transit or upon deposition (Lal 2003). However, the degree to which soil erosion contributes to atmospheric CO_2 depends on several additional factors. Erosion can alter SOC mineralization and stabilization at both eroding and depositional sites, for example by burying and partially preserving SOC at the depositional site (Billings et al., 2010; Dialynas et al., 2016). Oxidation of eroded SOC is, therefore, only one component of net SOC change (Van Oost et al., 2012). Stallard (1998) first introduced the concept of new SOC production at an eroding site, a process which can balance the oxidation of eroded SOC (Berhe et al., 2007; Billings et al., 2010; Dialynas et al., 2016; Fang et al., 2006; Harden et al., 1999; Jenerette and Lal 2007; Liu et al., 2003; Quine and Van Oost 2007; Rosenbloom et al., 2006; Smith et al., 2001; Van Oost et al., 2007). Global estimates of the carbon sink strength of erosion and deposition vary widely. Several studies suggest that soil net erosion and deposition may result in a small net carbon sink, perhaps up to about 0.1 Pg C per year (Van Oost et al., 2007), although Berhe et al. (2007) suggest a modern erosion-induced carbon sink strength of about 0.7 to 1 Pg C per year. Wang et al. (2017) estimate a cumulative offset of atmospheric carbon of 78 ± 22 Pg C

[1] Carbon dioxide equivalent (CO_2e): Amount of CO_2 that would produce the same effect on the radiative balance of Earth's climate system as another greenhouse gas, such as methane (CH_4) or nitrous oxide (N_2O), on a 100-year timescale. For comparison to units of carbon, each kg CO_2e is equivalent to 0.273 kg C (0.273 = 1/3.67). See Preface, p. 5, for details.

due to agriculturally enhanced erosion during the period 6000 BC to AD 2015, which represents approximately 37 ± 10% of carbon emissions linked to contemporary anthropogenic land-cover change. Carbon burial rates have increased by a factor of 4.6 since AD 1850, consistent with erosion-induced carbon fluxes occurring disproportionately in recent centuries. Extrapolating globally, Billings et al. (2010) suggest an upper limit of a maximum net global sink of 3.1 Pg C per year (if all eroded carbon were protected from oxidation) and a net source of 1.1 Pg C per year if all eroded carbon were oxidized.

Estimating the rates of the erosion-induced redistribution of soil carbon has many uncertainties (Berhe et al., 2007; Regnier et al., 2013). These uncertainties derive from 1) the dynamics of eroded and deposited SOM (Hu and Kuhn 2014); 2) the texture and mineralogy of the soil being eroded; 3) the geomorphological nature and potential for decomposition in depositional environments; 4) the history and future of land uses, especially in intensively managed landscapes such as harvested forests and agriculture (Papanicolaou et al., 2015); and 5) changes to climate and hydrological cycles, including the timing and frequency of extreme events. Additional watershed-based studies, experimental studies, and modeling can address these uncertainties.

12.3 Modeling SOC Dynamics

At the global scale, the response of SOC to the influences of land use, disturbances, and climate change is projected using ESMs, which include simplified versions of soil carbon cycling models (Harmon et al., 2011; Tian et al., 2015). These early soil carbon models (e.g., CENTURY, Bolker et al., 1998; RothC, Gottschalk et al., 2012) largely assume exchanges of carbon between soil carbon pools are first-order exchanges defined by pool turnover times (Todd-Brown et al., 2013), and such assumptions (and model frameworks) continue into contemporary large-scale ESMs such as the Community Land Model (Huang et al., 2018) or the E3SM Land Model (Tang and Riley 2016). However, different models use different strategies to simplify and represent the complex cycling processes that were discussed in Section 12.2, p. 472; thus, model simulation results tend to diverge. For example, model outputs can vary widely in their projections of global carbon stocks and microbial respiration (Tian et al., 2015) based on nonmodeled outputs such as deep carbon storage and wetland carbon storage. The addition of land use to some models has indicated that soils previously projected to be sinks for CO_2 may actually be sources (Eglin et al., 2010). Because SOC stocks are so large compared to other global compartments (e.g., vegetation and atmosphere), the wide variations in projections of SOC stocks contribute a great deal of uncertainty to future carbon cycle projections (Todd-Brown et al., 2013). Wider adoption of global data products including the Harmonized World Soil Database and SoilsGrid (FAO/IIASA/ISRIC/ISSCAS/JRC 2012; Hengl et al., 2014) may facilitate the development of new tools to better integrate both local SOC observations (Dietze et al., 2014; Xia et al., 2013; Xu et al., 2006) and global data products into future models (Hararuk et al., 2014).

At a finer scale, the recognition that small-scale processes, including microbial respiration, nutrient limitation, and soil microclimate (Luo et al., 2016; Tian et al., 2015), affect overall soil carbon fluxes has prompted the emergence of microbially explicit and process-rich models for soil carbon cycling (Manzoni and Porporato 2009; Sulman et al., 2014; Tang and Riley 2014; Wieder et al., 2013). Models that include the size of the microbial biomass, microbial dormancy, and enzyme functions (Wang et al., 2014) are beginning to represent previously ignored processes such as priming (accelerated decomposition of stable carbon), mineral association, and temperature sensitivities, as well as their feedbacks to the Earth's physical system in the form of altered GHG emissions. The most recent soil-specific models, such as the Millennial Model (Abramoff et al., 2018), further classify SOC into measurable physicochemical categories (e.g., mineral-associated carbon, carbon physically entrapped in aggregates, dissolved carbon, and fragments of plant detritus) and include explicit processes regulating the transfers of carbon between pools, in contrast to the earlier models based on empirical turnover times (Abramoff et al., 2018).

These modeling types reflect very different scales, with ESMs simulating kilometer-scale landscapes and the more process-rich models simulating regional processes at finer scales such as centimeters to meters. Bridging these scales requires further empirical understanding and new mathematical frameworks (e.g., Wang et al., 2017). As models continue to advance, other challenges include determining which new models and approaches can be parameterized with empirical data and used for larger-scale decision making.

12.4 North American and Regional Context

12.4.1 United States

Scientists have used several approaches to estimate U.S. SOC stocks. These stocks may be aggregated in specific land areas such as geopolitical boundaries (i.e., states) or Land Resource Regions, or they may be grouped by soil-order or land-cover classes (Guo et al., 2006; Wills et al., 2014). Most efforts have developed estimates for the conterminous United States (CONUS), but results vary based on methods and assumptions. Guo et al. (2006) estimated SOC stocks for CONUS as between 30 and 150 Pg (0 to 2 m in depth) by soil order using the State Soil Geographic database (STATSGO; USDA Soil Conservation Service 1993) and another 23 to 94 Pg C stock as inorganic carbon within the top 2 m of surface. Compared with CONUS, fewer studies have estimated soil carbon stocks for Alaska. Mishra and Riley (2012) estimated stocks in Alaska as 77 Pg C, an update from the value of 48 Pg estimated by Bliss and Maursetter (2010). The U.S. Geological

Table 12.1. Estimates of Soil Carbon Storage in the Conterminous United States in Different Land-Use Classes[a–d]

Land Cover	Soil Organic Carbon (from RaCA[e])	Soil Organic Carbon (Bliss et al., 2014)	Soil Organic Carbon (Sundquist et al., 2009)	Soil Organic Carbon (Other Estimates)
Forests and Woodlands	20	13.1	25.1	28[f]
Agriculture	13	13.4	27.4[d]	
Shrublands		5.6	9.7	
Urban		3.3		1.9[g]
Wetlands	14	8.9		13.5[h] – 11.5[i]
Rangelands (+ Pasture)	19	12.3	11.2[d]	
Totals	65	57.2[j]	73.4	

Notes

a) Storage measured in soil down to 1 m in depth.

b) All values are in petagrams of carbon (Pg C).

c) No total is given for "Other Estimates" values because the values do not represent all land-use classes and some land-use classes likely overlap (e.g., urban is partially accounted for in agriculture [see d] and developed; range estimates likely include some agricultural land).

d) "Agriculture" is listed in Sundquist et al. (2009) as "agriculture and developed"; "rangelands and pasture" is listed as "other" and includes all grasslands.

e) RaCA, U.S. Department of Agriculture's Rapid Carbon Assessment.

f) Domke et al. (2017).

g) Pouyat et al. (2006).

h) From the *Second State of the Carbon Cycle Report* (SOCCR2), Ch. 13: Terrestrial Wetlands, p. 507.

i) Nahlik and Fennessy (2016).

j) Total soil profile of carbon is 73 Pg.

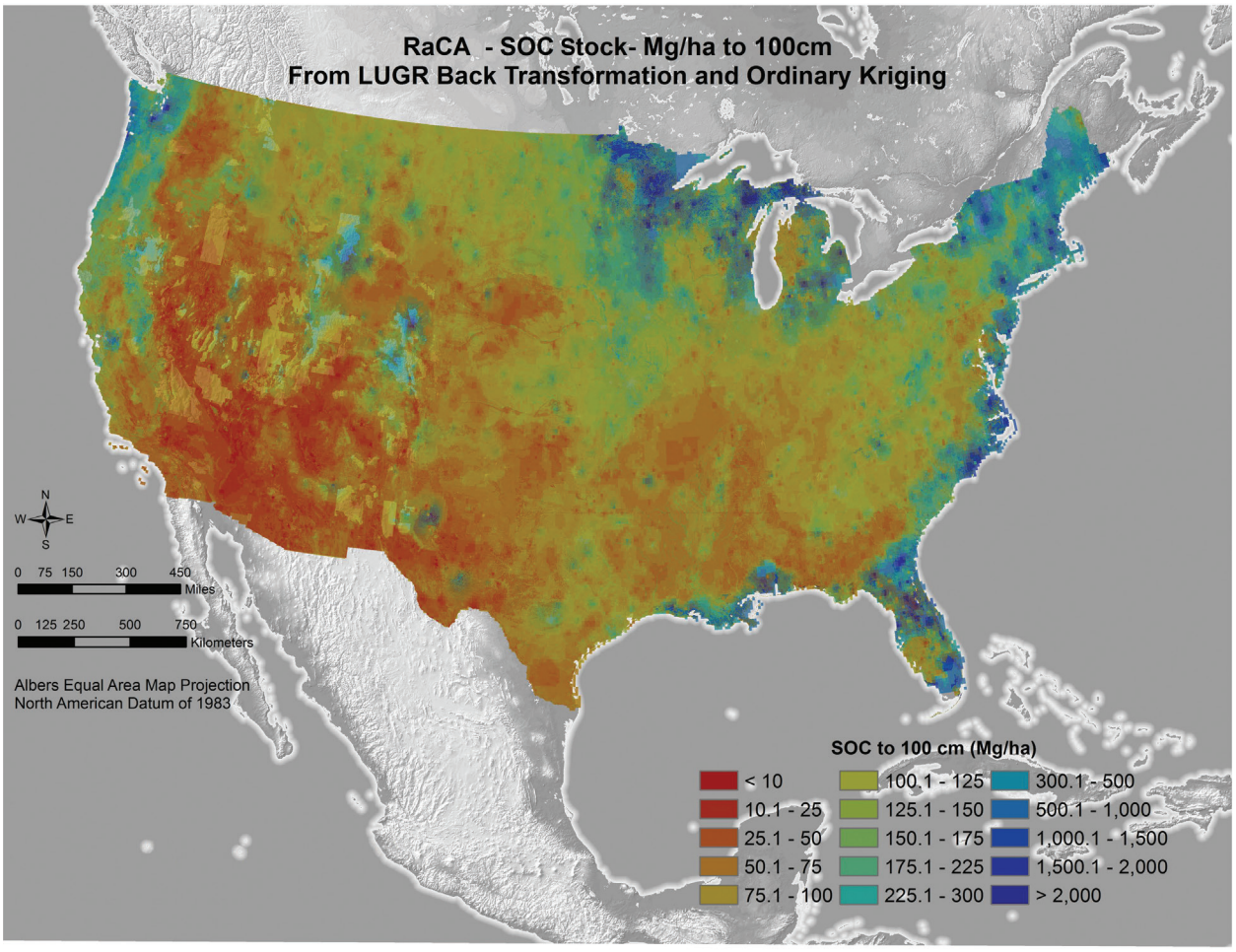

Figure 12.2. Rapid Carbon Assessment (RaCA) of Soil Organic Carbon (SOC) Stock Values. Data are in megagrams (Mg) of carbon per hectare (ha) to 100 cm. Soil group strata and land use and land cover (LULC) strata were linked together into a LULC-Soil Group Combination, designated as "LUGR." Prepared using the geometric mean of pedon stocks according to RaCA methodology. [Figure source: Reprinted from U.S. Department of Agriculture Natural Resources Conservation Service, Soil Survey Staff, RaCA project. Prepared by Skye Wills, 2016]

Survey (USGS) calculated CONUS SOC storage as 77.4 Pg C from the Soil Survey Geographic (SSURGO) database, developed by the USDA Natural Resources Conservation Service (NRCS). This information is supplemented with data from the Digital General Soil Map of the United States (STATSGO2; catalog.data.gov/dataset/u-s-general-soil-map-statsgo2-for-the-united-states-of-america; Sundquist et al., 2009; see Table 12.1, p. 479).

The NRCS's recent RaCA project captures information on the carbon content of soils across CONUS at a relatively uniform point in time (Soil Survey and Loecke 2016). A secondary goal was to capture SOC stocks in different kinds of soils and land uses. For this assessment, RaCA collected 144,833 samples from the upper 1 m of 32,084 soil profiles at 6,017 randomly selected locations across the United States. Independently developed soil groups for each RaCA region were combined with land-use, land-cover information, yielding an estimate of the total carbon stock across CONUS of 65 Pg C (see Figure 12.2, this page). Different estimates of soil carbon pools are expected to differ; individual soil and land-cover classes have different levels of uncertainties surrounding their carbon pool estimates, and errors

can include land-classification differences and different ways of aggregating sparse data. For example, Domke et al. (2017) used the USDA Forest Service's Forest Inventory and Analysis (or FIA) data to project SOC density in CONUS forest types and parts of Alaska and compared regional projections to those from RaCA. These modeled SOC density projections were substantially smaller than those of RaCA for most NRCS Land Resource Regions, at times by more than a factor of three.

Carbon storage in interior CONUS wetlands are assessed (see Ch. 13: Terrestrial Wetlands, p. 507) using a combination of NRCS SSURGO data and the U.S. Fish and Wildlife Service's (USFWS) National Wetland Inventory. These estimates of the upper 1 m indicate that terrestrial wetlands store about 13.6 Pg C, a value very similar to that of Nahlik and Fennessy (2016), who reported a value of 11.5 Pg. Storage of carbon in CONUS saline wetlands is significantly lower. Estimates of tidal wetland soil stocks along the freshwater-to-saline transition area plus the seagrass soil stocks are 0.8 Pg C for "blue carbon" ecosystems (see Ch. 15: Tidal Wetlands and Estuaries, p. 596). Given that more than half the historical U.S. wetland area has been lost due to anthropogenic activities, further loss of wetland soils represents a key vulnerability that could result in a net transfer of carbon from the soil to the atmosphere.

12.4.2 Mexico

The most recent estimate of soil carbon stocks in Mexico is reported to a depth of only 30 cm. According to Jobbágy and Jackson (2000), the top 20 cm of soil typically represents 40% of total soil carbon stocks averaged across vegetation communities in Mexico. At 9.13 Pg C in the top 30 cm, this reported SOC stock is 73% of the country's total terrestrial stock (CONAFOR 2010), but a conservative estimate of SOC stocks to 1 m in depth might be 18 Pg C, assuming that the top 30 cm represents about half the total soil carbon stocks. However, this estimate remains highly uncertain as acquisition of field data to fill data gaps (e.g., bulk density measurements) and spatial extrapolation methods continue to evolve (de Jong et al., 2010). For example, simply using different versions of land-cover maps for spatially extrapolating mean SOC values results in significant differences for semitropical low forests and mangroves (Paz Pellat et al., 2016). Despite these issues, almost half (48%) of Mexico's SOC appears to be contained in forests, especially the dry deciduous, semi-evergreen, and oak forests (see Tables 12.2, this page, and 12.3, p. 482). Furthermore, grazing lands accounted for 23% of the total SOC stock, mostly due to their extensive area. Finally, despite the relatively low soil carbon density of shrublands, they were extensive enough to account for 7% of the total SOC stock (Paz Pellat et al., 2016).

Table 12.2. Soil Organic Carbon Distribution in Mexico by FAO FRA[a] Classes[b]

FAO FRA Classes[a]	Area in Millions of Hectares	Petagrams of Carbon
Forestlands	65	4.3
Other Forestlands	20	0.6
Other Lands	108	4.1
Planted Forest	0.33	< 0.01
Totals	**194**	**9.1**

Notes

a) Global Forest Resources Assessment (FRA) of the United Nations Food and Agriculture Organization (FAO).

b) From Paz Pellat et al. (2016).

Table 12.3. Soil Organic Carbon Distribution in Mexico for Vegetation Types with Top Five Highest Total Soil Carbon Estimates[a]

Vegetation Types (Top Five)	Area in Millions of Hectares	Teragrams of Carbon	Percent of Total
Grazing Lands	50	2,115	23
Deciduous Dry Forest	14	690	8
Desert Microphyll Shrub	22	600	7
Medium Semi-Evergreen Forest	5	570	6
Oak Forest	11	564	6

Notes

a) From the National Institute for Statistics and Geography of Mexico for 2007 (from Paz Pellat et al., 2016).

At the national scale, CO_2 fluxes from mineral soils to the atmosphere were estimated as 30.2 Tg CO_2 per year, mostly from deforestation of secondary oak, pine-oak, and tropical dry forests (de Jong et al., 2010). About 10% of Mexico's land is strongly affected by soil erosion, with about 36% remaining stable (Bolaños-González et al., 2016).

Temperate forests in Mexico are potential areas of carbon sequestration because about 10% of total GHG emissions in Mexico are attributed to land-use change from opening new areas to cultivation and logging. Tropical forests in Mexico also experience much of the same pressures of land-use change, but they occur over stronger gradients of precipitation. Land-use change from forest to pasture appears to interact strongly with precipitation. For example, dry tropical forest conversion to pasture may increase SOC (3.7% at 788 mm per year), yet this same land-use change appears to decrease SOC as precipitation increases (–0.2% at 2,508 mm per year; –2.2% at 4,725 mm per year; Campo et al., 2016). Mangroves in Mexico have the highest density of soil carbon (364 Mg C per hectare), located throughout Mexico's extensive coastline and riverine systems. A variety of disturbances affect mangroves and, as in many parts of the world, include erosion, increasing sea level change, and salt intrusion (Gilman et al., 2008). Due to the difficultly in sampling these soils, few estimates are available, especially if attempting to quantify this stock to the bottom of the organic layer. Nevertheless, the Gulf of Mexico region generally has the highest carbon stocks (1,300 Mg C per hectare) of SOC compared with those of the other regions in Mexico (100 to 1,100 Mg per hectare; Herrera Silveira et al., 2016).

12.4.3 Canada

Canada has a total land area of 998.5 megahectares (Mha) that contains 72.2 gigatons of carbon (Gt C) to a depth of 30 cm (Tarnocai 1997). The total of 55.2 Mha of land currently used for agriculture contain about 4.14 Gt C to a depth of 30 cm and 5.5 Gt to 1 m. As about 80% of agricultural land is located in the Canadian Prairies, most (approximately 88%) SOC is also found in Prairie soils, which are mostly carbon-rich Chernozemic soils developed under grassland. Tarnocai (1997) estimated a total of 262.3 Pg C in soils within the tundra, forest, and agricultural regions of Canada. Over half the carbon (147.1 Pg C; Tarnocai 2006) is in organic (peat) soils, some of which are affected by permafrost. Total soil carbon estimates for Canada likely will increase as knowledge of deep carbon stocks in permafrost soils increases (Hugelius et al., 2014). For example, Kurz et al. (2013) estimated that soils in Canada's boreal forest region alone contain 208 Pg C, which is about 80% of the Tarnocai (1997) estimate of the total carbon stocks in Canada. Of this 208 Pg, the majority (137 Pg) of the boreal soil carbon stocks are in the deep organic soils of the country's extensive peatlands, and the remainder (71 Pg) are in upland

Table 12.4. Estimates of Soil Carbon Storage in Canada[a–b]

Land Cover	Soil Organic Carbon
Organic (Peat) Soils	147.1[c], 137[e]
Agriculture	5.5[d]
Boreal Forest Region	208[e, f]
Upland Forest Soils	71[e]
Total	262.3[c, g]

Notes

a) Storage measured in soil down to 1 m in depth.

b) Values in petagrams.

c) Tarnocai (2006).

d) Tarnocai (1997).

e) Kurz et al. (2013).

f) Note that this overlaps with estimates of organic peat soil carbon.

g) Columns do not add up due to overlap in categories.

forest soils that often have thick organic soil horizons (42 to 55 Mg C per hectare; estimated from Letang and de Groot 2012) that overlay the mineral soil (Kurz et al., 2013; see Table 12.4, this page).

Canadian forest soil carbon research over the last decade has focused on understanding the dynamics of SOC as influenced by 1) mosses (Bona et al., 2013, 2016); 2) forest composition and soil taxonomy (Laganiere et al., 2015; Shaw et al., 2008, 2015); 3) invasive earthworms (Cameron et al., 2015); 4) response to temperature changes (Laganiere et al., 2015; Smyth et al., 2011); 5) response to wildfire, specifically in peatlands (Granath et al., 2016; Kettridge et al., 2015); and 6) recovery patterns (Ward et al., 2014). Under development is a national peatland carbon modeling system (Webster et al., 2016) that will fill information gaps previously identified, including a peatland-type map; landscape-scale modeling of forested, treed, and nontreed peatland types; water table fluctuation in response to climate change; and CH_4 fluxes (Shaw et al., 2016). Eventually, responses to permafrost thaw, wildfire, and anthropogenic disturbances will be included (Shaw et al., 2016; Webster et al., 2016).

Several new spatial products and databases have improved the understanding of relationships among vegetation types (Beaudoin et al., 2014; Thompson et al., 2016) and changes in disturbance-type patterns (Hermosilla et al., 2016), improving accuracy and enhancing the ability to scale up and integrate results from fine-scale to landscape-scale studies reporting national GHG emissions.

The 55.7 Mha of land that currently are used for agriculture in Canada are estimated to contain about 4.3 Pg C to a depth of 30 cm and 6.6 Pg C to 1 m using the Canadian Soil Information Service (CanSIS) National Soil Database. As of 2013, Canadian agricultural land removed 11 Tg CO_2 per year, an amount which represents about 2% of the total national GHG emissions (ECCC 2015). This is due largely to a reduction in the use of summer fallow lands and increased adoption of no-till practices in the Canadian Prairies. However, this value has declined from the reported 13 Tg in 2005 because changes in SOC stocks and fluxes tend to reach equilibrium at some point after a change in conditions.

12.4.4 Arctic and Boreal Ecosystems

Arctic and boreal ecosystems cover about 22% of the global land surface (Chapin et al., 2000) and contain 1,035 ± 150 Pg C in the upper 3 m of surface soil (Hugelius et al., 2014), amounts which equal about 33% of the total global surface SOC pool (Jobbágy and Jackson 2000; Schuur et al., 2015). The presence of permafrost and waterlogged soils in boreal and Arctic soils has allowed the accumulation of large quantities of carbon in this biome (McGuire et al., 2009; see Ch. 11: Arctic and Boreal Carbon, p. 428, for more details). Deep soils (>3 m in depth) contain significant stocks estimated between 210 ± 70 Pg C and 456 ± 45 Pg C, particularly in carbon-rich Pleistocene-age sediments called "yedoma" found in unglaciated parts of Alaska and Siberia, as well as in their alluvial deposits (Hugelius et al., 2014).

The changing disturbance regime can strongly affect soil carbon storage and flux. Permafrost thaw (Schuur et al., 2015) is tied to changes in the timing, frequency, and severity of wildfires

(Chapin et al., 2010; Kasischke et al., 2010), plant community composition (Mann et al., 2012), and alterations in the hydrological cycle (Jorgenson et al., 2001, 2010; Roach et al., 2013). Thaw will affect both storage and fluxes of carbon as the climate continues to warm. An estimated 5% to 15% of the terrestrial permafrost carbon pool is thought to be vulnerable to decomposition and release to the atmosphere, based on a synthesis of experimental studies, ecosystem models, and expert assessments (Schuur et al., 2015). Carbon loss from peatlands has shown large responses to water table fluctuations (Waddington et al., 2015), wildfire events (Turetsky et al., 2011), and permafrost thaw (Jones et al., 2017; Wisser et al., 2011). Key uncertainties as to the future of carbon storage in Arctic and boreal regions include the extent to which plant community productivity will respond to elevated CO_2 (McGuire et al., 2009), whether landscapes will become wetter or drier in the future (Schuur et al., 2015), the magnitude of winter fluxes (Commane et al., 2017), and the extent of the permafrost carbon feedback (Schaefer et al., 2011; Schuur et al., 2015).

12.5 Societal Drivers, Impacts, and Carbon Management

12.5.1 Agriculture

Because more than 50% of the Earth's vegetated surface is dedicated to agriculture (e.g., cropland and grazing land), understanding the role of agricultural management on SOC stocks is critical (see Ch. 2: The North American Carbon Budget, p. 71). Virtually all management choices (e.g., crop type, rotation, tillage, fertilization, irrigation, and residue management) will affect carbon inputs (e.g., crop residues and manure) and the decay rate or erosional loss of SOM (Paustian et al., 1997; Smith 2008). In most cases, SOC changes occur slowly and short-term (annual) changes are difficult to measure, but studies from long-term experiments, together with improved predictive models, provide a basis for guiding management and policies to improve SOC stocks (NAS 2010; Ogle et al., 2014; Paustian et al., 2016). Causes of SOC loss include 1) reduced biomass carbon inputs; 2) enhanced erosion and leaching; and 3) increased decomposition rates due to tillage disturbance (Paustian et al., 2016). A meta-analysis for Canadian soils reported that, when native soil was converted to agricultural land, there was an average loss of 24% ± 6% of soil carbon (VandenBygaart et al., 2003). Globally, agricultural soils have lost, on average, 20% to 45% of their original top soil carbon (0 to 30 cm) but with much higher losses in cultivated organic soils and where extensive erosion has occurred (Don et al., 2011; Ogle et al., 2005). Following restoration of perennial forest and grassland vegetation on annual cropland (e.g., for soil restoration or retiring marginal lands from production), much of the lost soil carbon stocks eventually can be recovered. Conversion of annual cropland to perennial grassland in temperate environments increased soil carbon stocks, on average, by 13% to 16%, with greater relative increases occurring in more mesic climates (Ogle et al., 2005).

In recent decades, SOC stocks in agricultural soils in the United States and Canada have stabilized and in some cases begun to increase (Follett et al., 2011; U.S. EPA 2015) as new conversion of land to agricultural use has largely halted and adoption of soil conservation practices and crop yields have increased (Chambers et al., 2016; Johnson et al., 2006). Effects of agriculture on soil carbon stocks, along with effects of conservation measures, are reviewed and quantified in Angers and Eriksen-Hamel (2008), Hutchinson et al. (2007), Luo et al. (2010), Palm et al. (2014), Paustian et al. (2016), Powlson et al. (2014), and many others. Improved residue management, added forage in crop rotations or adoption of agroforestry, double-cropping, conservation reserve planting, increased use of perennials in rotation, and use of practices that increase plant growth such as effective fertilization are successful in increasing soil carbon (Hutchinson et al., 2007; Luo et al., 2010; Palm et al., 2014), especially if more than one practice is used. In Canada, the wide adoption of reduced tillage and summer fallow over many regions has resulted in soil carbon increases and reduced erosion

(Agriculture and Agri-Food Canada 2016; Soil Conservation Council of Canada 2016).

An analysis of no-till only versus conventional till by Palm et al. (2014) found that carbon gains occurred in only half the paired comparisons and that increased residue retention had a greater effect on soil carbon than reduced tillage. Powlson et al. (2014) argue that adoption of no-till agriculture can improve crop production and reduce erosion in many cases, but it may not have significant effects on carbon sequestration. However, a meta-analysis by Kopittke et al. (2017) saw an overall small positive (+9%) effect of conversion to no-till from conventional till methods. Most analyses of tillage effects do not account for SOC erosion. Montgomery (2007) calculated a mean erosion rate difference between conventional agriculture and no-till agriculture of about 1 mm per year. Although this eroded soil causes a net movement of carbon from the site with associated negative effects on soil fertility and health, this movement might not represent a net loss of soil carbon globally and could represent a net sink, because the eroded carbon can be buried and therefore protected. Meanwhile, carbon accumulation can continue in the site from which the erosion originally occurred via the usual processes of additions and transformations of plant residues (Wang et al., 2017).

Estimates of the current SOC balance for U.S. agricultural lands suggest a small net sink on long-term cropland (6.4 Tg C per year) and on land recently converted to grassland (2.4 Tg C per year), while small net losses of SOC were estimated for long-term grassland (3.3 Tg C per year) and land recently converted to cropland (4.4 Tg C per year; U.S. EPA 2015). A similar picture appears for Canadian agricultural soils with an estimated net sink of about 3 Tg C per year (ECCC 2015). A full soil carbon inventory for Mexican agricultural soils is still in progress; however, with ongoing forest conversion to agricultural uses (see Section 12.4.2, p. 481), there likely is a substantial loss of SOC due to agricultural activities.

Other chapters present more information on management of agricultural soils and its effects on carbon (see Ch. 5: Agriculture, p. 229; Ch. 7: Tribal Lands, p. 303; and Ch. 10: Grasslands, p. 399).

12.5.2 Forestry

A wide variety of forest management practices affect around 204 Mha of timberlands in CONUS (see Ch. 9: Forests, p. 365). Those practices typically involve a combination of harvesting, stand regeneration, and stand tending. The intensity of those practices and their resulting effects on soils depend on landowner management objectives.

To date, most research on forest harvest effects on soil carbon has suggested that mild to moderate intensity harvesting does not cause measurable changes in upland soils (Johnson and Curtis 2001), but that intensive harvesting and plantation management may cause reductions in mineral soil carbon (Buchholz et al., 2014; Johnson and Curtis 2001), especially if imposed on old-growth natural stands. A meta-analysis of studies measuring effects of forest harvest on soil carbon stocks by Nave et al. (2010) found that while forest floor carbon generally was reduced after harvest, mineral soil carbon was less affected, although certain soil orders were more susceptible to mineral soil carbon loss than others. Forest soil carbon stores have the ability to recover to preharvest stages, although recovery might take decades (Nave et al., 2010) to a century or more (Diochon et al., 2009); thus, rotation length plays a significant role in the degree of harvest impacts on soil carbon. Several chronosequence studies have observed reductions in mineral-bound carbon pools in successional stands decades after harvesting (Diochon et al., 2009; Lacroix et al., 2016; Petrenko and Friedland 2015). Because this timing of carbon loss corresponds to periods of high nutrient demands during biomass re-accumulation, the cause could be mining of SOM by plants and mycorrhizal fungi to alleviate nutrient limitation. Dean et al. (2017) argue from a modeling standpoint that there are more significant losses of soil carbon with forest harvest of primary forests when calculated over centuries, but this model result is not supported by empirical studies.

Afforestation and agroforestry (the practice of integrating woody vegetation with crop and/or

animal production systems) have been cited as having potential for increasing soil carbon sequestration (IPCC 2000; Upson et al., 2016). Several meta-analyses conducted on afforestation effects on former croplands have produced a general consensus that soil carbon gains may take more than 30 years to be measurable (Barcena et al., 2014; Li et al., 2012; Nave et al., 2013) but can increase carbon stocks by 19% to 53% (Guo and Gifford 2002; Nave et al., 2013). However, while tree establishment in both grasslands and croplands showed greatly increased aboveground biomass carbon storage, meta-analysis of studies found that tree establishment on pastureland led to losses or no changes in soil carbon (Shi et al., 2013).

12.6 Synthesis and Outlook

Soil carbon is vulnerable to both pervasive warming and moisture disturbances, as well as to land-use decisions, all of which can strongly affect soil carbon contents. In northern latitudes, which are particularly vulnerable to soil carbon loss, some of the fastest warming trends (Cohen et al., 2014) and largest carbon stocks (Ping et al., 2008) occur. A significant portion of northern soil carbon is stored as organic peat horizons, which play a pivotal role in insulating permafrost from temperature changes but are particularly sensitive to changes in soil moisture (Johnson et al., 2013). Thus, the feedbacks among warming, moisture, and wildfire have important consequences to the carbon cycle at a global scale (Olefeldt et al., 2016). Meanwhile, localized "hotspots" for soil carbon storage, while also vulnerable to warming and soil moisture, can be sensitive to management practices as well and, therefore, can offer potential mitigation opportunities to avoid carbon emissions. For example, maintaining high water tables in carbon-rich peatlands potentially avoids carbon emissions that otherwise would accompany drainage.

Management options for actively sequestering carbon into soil are important opportunities for climate mitigation, but several issues arise before there is confidence in the outcome for a given soil under a given management setting. Topographical and mineralogical characteristics and disturbance histories (e.g., fire-return interval and land-use change history) likely influence the net balance between input and loss and yet are highly variable across North America. Strategic experimental designs with consistent oversight and methodologies could constrain the uncertainties and understanding of the processes that control carbon storage. Building spatially and temporally explicit databases could improve process-based models to provide better estimates for soil carbon trajectories and thereby empower land managers to chart the trajectory of soil carbon.

Increasingly, the development of policies to 1) promote improved soil health (Kibblewhite et al., 2008; Vrebos et al., 2017), 2) encourage soil carbon sequestration for GHG mitigation (Chambers et al., 2016; Follett et al., 2011), and 3) satisfy consumer demands for more sustainable products (Lavallee and Plouffe 2004) will demand strong scientific support for improved understanding of SOC dynamics, new technologies to increase SOC stocks, and decision-support tools to effectively assess options and monitor progress. Along with new research on more conventional practices to build soil carbon (e.g., improved rotations, reduced tillage, and cover crops), scientists are investigating newer practices and technologies to increase SOC stocks, including 1) applying biochar (Woolf et al., 2010) and compost (Ryals et al., 2015), 2) using deep tillage to increase the total depth and storage of SOC-rich soil (Alcantara et al., 2016), 3) deploying new crop varieties with increased allocation of carbon below ground and deeper into the soil profile (Paustian et al., 2016), and 4) planting perennial plants in place of annual crops (Cox et al., 2006). New research and best practices in forestry such as selective harvesting and residue management (Peckham and Gower 2011), tailored for particular soils (Hazlett et al., 2014), also have the potential to increase carbon retention in forest soils. As new knowledge is generated about the applicability of various practices in different environments, incorporating this new information into improved decision-support tools (see Ch. 18: Carbon Cycle Science in Support of Decision Making, p. 728) will guide land managers, industry, policymakers, and other stakeholders in building heathier soils that are rich in organic matter.

SUPPORTING EVIDENCE

KEY FINDING 1

Estimates for soil carbon stocks in the conterminous United States plus Alaska range from 142 to 154 petagrams of carbon (Pg C) to 1 m in depth. Estimates for Canada average about 262 Pg C, but sampling is less extensive. Soil carbon for Mexico is calculated as 18 Pg C (1 m in depth), but there is some uncertainty in this value (*medium confidence*).

Description of evidence base

The value range of soil carbon to a depth of 1 m for the United States is based on several compilations: Alaska is estimated in Mishra and Riley (2012) as 77 Pg C, an increase from the value reported by Bliss and Maursetter (2010) of 48 Pg. The sampling for the Mishra and Riley (2012) estimate is quite extensive, and land types for areal weighting are well known and documented. Modern estimates for the conterminous United States (CONUS) span the range from the U.S. Geological Survey (USGS) estimate of Sundquist et al. (2009) at 77 Pg C and the Rapid Carbon Assessment (RaCA, initiated by the Soil Science Division of the U.S. Department of Agriculture's National Resources Conservation Service in 2010) estimate (Soil Survey and Loecke 2016) at 65 Pg C (see Table 12.1, p. 479). The RaCA estimate is based on 144,833 soil samples and extrapolation using detailed soil maps. The soil carbon value of 9 Pg C for Mexico is based on Paz Pellat et al. (2016), but that estimate is based on sampling to a depth of only 30 cm. Based on conversion factors in Jobbágy and Jackson (2000), a conservative extrapolation to 1 m yields a value of 18 Pg C. The estimates for Canada are from Tarnocai (1997, 2006). This assessment recognizes that 1 m is a very arbitrary depth to consider; Batjes (1996) reported a 60% increase in the global soil organic carbon (SOC) budget when the second meter of soil was included.

Major uncertainties

There is medium high confidence in the estimates from CONUS due to new extensive and intensive sampling, although estimates for specific land-use classes still vary with different estimates. Confidence is relatively high for estimates in the agricultural areas of Canada but lower for forested areas. In Canada, uncertainty for the large peatlands areas in the boreal and Arctic regions is high due to low-sampling intensity and low-resolution mapping of peatland types. Uncertainty for estimates from Mexico are likely high due to low sampling coverage, and available data are only to a depth of 30 cm.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Soil carbon was extensively sampled in three independent studies for CONUS, so the confidence for the range of values reported here is very high. Due to the complex nature of estimating soil carbon in boreal and peat regions, the uncertainty is greater surrounding values for Canada. There is low confidence in values reported for Mexico as sampling is not as extensive and the depth of sampling is not as great.

Summary sentence or paragraph that integrates the above information

The estimates of total soil carbon stores are reasonably accurate for CONUS and Canada but are less accurate for Mexico.

KEY FINDING 2

Most Earth System Models (ESMs) are highly variable in projecting the direction and magnitude of soil carbon change under future scenarios. Predictions of global soil carbon change through this century range from a loss of 72 Pg C to a gain of 253 Pg C with a multimodel mean gain of 65 Pg C. ESMs projecting large gains do so largely by projecting increases in high-latitude soil organic carbon (SOC) that are inconsistent with empirical studies that indicate significant losses of soil carbon with predicted climate change (*high confidence*).

Description of evidence base

A description of the scientific concerns with current ESMs is presented in He et al. (2016). They analyzed ^{14}C data from 157 globally distributed soil profiles sampled to a depth of 1 m to demonstrate that ESMs currently overestimate the soil carbon sink potential. Todd-Brown et al. (2014) also pointed out major sources of error in current ESMs and suggested that most ESMs poorly represented permafrost dynamics and omitted potential constraints on SOC storage, such as priming effects, nutrient availability, mineral surface stabilization, and aggregate formation. For example, many ESMs simulated large changes in high-latitude SOC that ranged from losses of 37 Pg C to gains of 146 Pg C. The poor performance of current ESMs can result from biases in model structure, parameterization, initial values of carbon pools, and other variables (Luo et al., 2016).

There is currently a great deal of controversy over how to improve the representation of soil carbon in models (Chen et al., 2015); several authors suggest that microbial dynamics, including the priming effect, need better representation (Georgiou et al., 2015; Sulman et al., 2014; Wieder et al., 2014), as does soil carbon response to nitrogen enrichment (Janssens and Luyssaert 2009; Riggs and Hobbie 2016). However, there is no evidence that suggests how much detail is needed to adequately represent future soil carbon dynamics and soil carbon pools.

Deep carbon (>1 m in depth) generally has been found to be more stable and resistant to management or climate change than carbon in surface soils (Rumpel and Kögel-Knabner 2010; Schrumpf et al., 2013), but, given that subsurface horizons contain more than half the soil carbon (Jobbágy and Jackson 2000), small changes could significantly affect carbon budgets. Although less well studied, deep carbon has been shown to be sensitive to management practices (Alcantara et al., 2016; Ward et al., 2016).

Microbial dynamics, including the priming effect, are key controls on soil carbon turnover (Bernal et al., 2016; Guenet et al., 2012). Carbon-use efficiency of different substrates by microbes might be a key factor in soil carbon stabilization (Cotrufo et al., 2013).

Major uncertainties

How much detailed information on microbial physiology, coupled carbon-nitrogen cycles, or other processes is needed to improve soil carbon models is not well known.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Models can be tested against empirical data, and they do not perform very well; thus, determining the accuracy of future projections is difficult.

Summary sentence or paragraph that integrates the above information

The poor performance of current ESMs can result from biases in model structure, parameterization, initial values of carbon pools, and other variables. Most ESMs poorly represent permafrost dynamics and omit potential constraints on SOC storage, such as priming effects, nutrient availability, mineral surface stabilization, and aggregate formation.

KEY FINDING 3

Soil carbon stocks are sensitive to agricultural and forestry practices and loss of carbon-rich soils such as wetlands. Soils in North America have lost, on average, 20% to 75% of their original top soil carbon (0 to 30 cm) with historical conversion to agriculture, with a mean estimate for Canada of 24% ± 6%. Current agricultural management practices can increase soil organic matter in many systems through reduced summer fallow, cover cropping, effective fertilization to increase plant production, and reduced tillage. Forest soil carbon loss with harvest is small under standard management practices and mostly reversible at the century scale. Afforestation of land in agriculture, industry, or wild grasslands in the United States and Canadian border provinces could increase SOC by 21% ± 9% (h*igh confidence*).

Description of evidence base

Converting native forests or pastures to cropland can reduce soil carbon by 42% to 59%, respectively (Guo and Gifford 2002). A meta-analysis for Canadian soils reported that, when native soil was converted to agricultural land, there was an average 24% loss of soil carbon (VandenBygaart et al., 2003). Estimates for Mexico also suggest that loss of soil carbon due to management remains significant (Huber-Sannwald et al., 2006).

Agricultural effects on soil carbon stocks, including effects of conservation measures, are reviewed and quantified in Angers and Eriksen-Hamel (2008), Hutchinson et al. (2007), Luo et al. (2010), Palm et al. (2014), Paustian et al. (2016), Powlson et al. (2014), and many others. Specific conservation measures for improved soil carbon retention have been shown to be effective in both Canada and the United States. In Canada, conservation measures, including reduced summer fallow and reduced tillage, have been widely adopted over many regions and have resulted in soil carbon increases and reduced erosion (Soil Conservation Council of Canada 2016). Agriculture and Agri-Food Canada (2016; AAFC) has 30 years of data showing that, in the Canadian Prairies, reduced tillage combined with reduced summer fallow have led to significant SOC increases. Improved residue management, including adding forage in crop rotations or adopting agroforestry, and practices that increase plant growth such as effective fertilization are effective in increasing soil carbon (Hutchinson et al., 2007; Palm et al., 2014). A meta-analysis by Angers and Eriksen-Hamel (2008) suggested that, although significant increases in surface soil carbon with reduced tillage are commonly observed, the slight decreases in soil below the plow layer also are common, thus making overall increases in total soil carbon profiles averaged across studies small but significant. In a more recent meta-analysis by Luo et al. (2010), increased soil carbon with reduced tillage was seen only for double-cropping systems, a finding which agrees with the AAFC result that reduced summer fallow and reduced tillage together caused significant increases in soil carbon.

Palm et al. (2014) point out serious methodological flaws with many tillage comparisons that include sampling by depth not equivalent soil mass, flaws which cause significant overestimates

of soil carbon in no-till soils with higher bulk densities. In their 2014 meta-analysis, about half the paired comparisons showed small increases in soil carbon from reduced till but half did not, suggesting that increased residue retention is more significant than reducing tillage. A similar meta-analysis by Kopittke et al. (2017) that also corrected for changes in bulk density found an overall small positive (+9%) effect of conversion to no-till practices from conventional till. Powlson et al. (2014) point out that the gains in surface soil carbon with adoption of no-till methods can improve crop production and reduce erosion in many cases, but the reverse can be true in cool, wet climates or the wet tropics.

Several meta-analyses of afforestation effects on former croplands have been conducted, and there is general consensus that soil carbon gains may take more than 30 years to be seen (Barcena et al., 2014; Li et al., 2012; Nave et al., 2013) and can increase carbon stocks by 19% to 53% (Guo and Gifford 2002; Nave et al., 2013).

Data on forest harvest effects are from a comprehensive meta-analysis by Nave et al. (2010), who report variable and low changes in mineral soil carbon stocks with forest harvest but significant decreases in forest floor carbon. Several chronosequences support this meta-analysis. Dean et al. (2017) argue from a modeling standpoint that there are significant long-term losses of soil carbon with forest harvest of primary forests; however, much of this argument is based on assumptions about the relationship between plant inputs and soil carbon sequestration that are not necessarily supported by empirical studies.

Wetland estimates are based on information in this report's (SOCCR2) two wetland chapters. All chapters showed findings of strong evidence that loss of wetlands is a significant factor for total soil carbon loss, given the very high carbon density of wetland soils.

Wear and Coulston (2015), using data from the National Greenhouse Gas Inventory (NGHGI), report annual forest carbon accumulation, including both sequestration and land-use transfers in the United States as 223 teragrams of carbon (Tg C) per year, roughly 0.5% of the stored forest carbon. This likely translates into increased soil carbon storage, although this distinction was not made in the analysis. Similar estimates have not been made for Canada or Mexico.

Major uncertainties

The certainty for forest harvest effects on soil carbon appears to be very robust and based on many studies across North America, although a recent modeling study suggests that these other studies, carried out over decades, miss a multicentury-scale slow loss of soil carbon with forest harvest. However, there are no data to support that model result. Uncertainty arises because there are few empirical studies that compare soil carbon stocks in true primary forests to forests that have undergone centuries-long harvest cycles.

Uncertainties for agricultural effects have to do with site-specific variation in management implementation and lack of knowledge of deep soil carbon dynamics. However, convergence of the different meta-analyses on similar figures and research in this field is quite extensive (Li et al., 2012).

The wetland estimate also is quite robust given the high sampling density of the National Wetland Condition Assessment (NWCA) of the National Aquatic Resource Surveys. The NGHGI estimate of forest cover increase is quite robust given the quality of input data.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

The meta-analyses of Nave et al. (2010, 2013) suggest very good agreement over forestry effects on soil carbon, although Dean et al. (2017) suggest that, over centuries, logging has had more significant effects on soil carbon. Given that the Dean et al. (2017) study is based on modeling with assumptions that are not supported in this analysis, such as that SOC is strongly related to biomass inputs, SOCCR2 is placing greater confidence in the Nave analyses (Nave et al., 2010, 2013).

The analysis by Paustian et al. (2016) suggests that there is some disagreement over agricultural management effects on SOC and that these effects are specific to local site and climatic conditions. The Li et al. (2012) meta-analysis suggests that afforestation of former croplands globally results in net SOC increases but that local results are so variable that local projection is difficult and results depend on soil type, management, and the type of tree species.

The wetland estimate is quite robust given the high sampling density of the NWCA.

Estimated likelihood of impact or consequence, including short description of basis of estimate

Conversion to agriculture is a significant source of greenhouse gases to the atmosphere and loss of soil carbon. However, across North America, mitigation strategies such as conversion to no-till or reduced-till methods, adoption of crop rotations that provide greater carbon inputs, increased residue retention, and the use of cover crops during fallow periods are reducing the impact of agriculture (Paustian et al., 2016). Similar results are seen in Canada (Soil Conservation Council of Canada 2016). Erosion of soil carbon from agricultural lands is still a significant concern (Montgomery 2007). Afforestation has caused increases in soil carbon across CONUS.

Summary sentence or paragraph that integrates the above information

Studies have shown that conversion of native land to agriculture significantly reduced soil carbon, although improved management of agricultural land has the potential to have significant positive effects on soil carbon reserves. While modeling exercises suggest that logging and management of primary forest cause a significant SOC loss, robust meta-analyses suggest that this loss is quite minimal with effective forestry management.

KEY FINDING 4

Large uncertainties remain regarding soil carbon budgets, particularly the impact of lateral movement and transport of carbon (via erosion and management) across the landscape and into waterways. By 2015, cumulative regeneration of soil carbon at eroded agricultural sites and the preservation of buried, eroded soil carbon may have represented an offset of 37 ± 10% of carbon returned to the atmosphere by human-caused land-use change (*medium confidence*).

Description of evidence base

Best estimates of the effects of erosion are summarized in Billings et al. (2010), Van Oost et al. (2007), and Wang et al. (2017). Erosion can significantly affect productivity in agricultural regions, and some authors have argued that loss of eroded carbon represents a true loss to the atmosphere (Lal and Pimentel 2008). However, work based on multiple eroding profiles indicates that approximately 26% of eroded SOC can be replaced at the eroding site, representing a

small but significant carbon sink (Van Oost et al., 2007). Harden et al. (1999) suggest that U.S. cropping patterns before 1950 likely resulted in about a 20% to 30% reduction of original SOC but that on-site recovery of soil organic matter (SOM) levels occurred after the 1950s. In Canada, VandenBygaart et al. (2012) also note a net carbon sink for eroded agricultural soils. Van Oost et al. (2007) suggest that replacement of eroded SOC, along with damped SOC mineralization upon burial, may combine to generate a small net carbon sink up to about 0.1 Pg C per year. Wang et al. (2017) calculate that cumulative, agriculturally accelerated erosion prompted SOC replacement and buried SOC preservation, representing an offset of 70 ± 16% of carbon emissions by anthropogenic land-cover change up to AD 1600; after this period, the cumulative value represented a smaller offset (37 ± 10% in 2015).

Major uncertainties

The fate of eroded agricultural soil can only be modeled, not directly measured, and the production of new soil carbon after exposure of new mineral surfaces also cannot be directly measured.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Erosion of soil is known to occur, but the fate of the eroded SOC is less clear. Currently, findings conclude that the eroded SOM appears to represent a small sink of carbon but that not all material is accounted for, and the geographic extent of full carbon budget studies is quite limited. Although subsurface soil carbon appears to be relatively stable, the responses to future changes in management and climate are not well understood.

Estimated likelihood of impact or consequence, including short description of basis of estimate

In the United States, conservation measures introduced after the Dust Bowl of the 1930s suggest that the potential for massive erosional losses of soil carbon are unlikely, but similar measures are not used in Mexico. In Canada, conservation measures including zero-till have been widely adopted over many regions and have resulted in soil carbon increases and reduced erosion (Soil Conservation Council of Canada 2016). Estimates for Mexico suggest that loss of soil carbon due to management practices remains significant (Huber-Sannwald et al., 2006).

Summary sentence or paragraph that integrates the above information

Large uncertainties remain in specific key areas, including the impact of lateral movement and transport of carbon through erosion and management.

KEY FINDING 5

Evidence is strong for direct effects of increased temperature on loss of soil carbon, but warming and atmospheric carbon dioxide increases also may enhance plant production in many ecosystems, resulting in greater carbon inputs to soil. Globally, projected warming could cause the release of 55 ± 50 Pg C over the next 35 years from a soil pool of 1,400 ± 150 Pg C. In particular, an estimated 5% to 15% of the peatland carbon pool could become a significant carbon flux to the atmosphere under future anthropogenic disturbances (e.g., harvest, development, and peatland drainage) and change in disturbance regimes (e.g., wildfires and permafrost thaw) (*medium confidence*).

Description of evidence base

Although many laboratory experiments have shown that soils respond to increased temperature with increased respiration, there are many potential causes for this increase, including increased belowground inputs (Giardina et al., 2014) or increased plant production (Phillips et al., 2016). A global meta-analysis has shown that soil respiration increases with temperature (Bond-Lamberty and Thomson 2010), but how much of this is due to turnover of new, labile plant inputs is unclear (reviewed in Bradford et al., 2016). Empirical relationships developed by Crowther et al. (2016) suggest that global soil carbon stocks in the upper soil horizons will fall by 30 ± 30 Pg C under a temperature increase of 1°C, and 55 ± 50 Pg C with expected warming in the next 35 years, depending on the rate at which the effects of warming are realized.

Many studies have suggested that peatlands and boreal ecosystems are particularly vulnerable to warming (Bridgham et al., 2008; Dise 2009; Hicks Pries et al., 2015; Koven et al., 2015) because of factors such as permafrost thawing and drying effects on decomposition (Ise et al., 2008), increased fire from drying (Turetsky et al., 2014), and poleward expansion of low-carbon ecosystems (Koven 2013). Thawing of sporadic and discontinuous permafrost may release up to 24 Pg C currently stored in boreal peatlands over decades to centuries (Jones et al., 2017). Wildfire combustion of organic soils across permafrost-dominated landscapes can produce carbon losses ranging from 2.95 ± 0.12 to 6.15 ± 0.41 kilograms of carbon per m^2, depending on the season (Turetsky et al. 2011).

Major uncertainties

Most laboratory experiments demonstrate that warming causes the loss of soil carbon, but how soils in natural ecosystems will respond to global warming is less predictable, given the different possible trajectories of plant production responses in different ecosystems and the possibility of increased plant production matching elevated soil respiration (Xu et al., 2016). Acclimation of soil microbes to warming could modulate the response of soils (Luo et al., 2001), although a meta-analysis (Wang et al., 2014) suggests that heterotrophic activity will not significantly acclimate to warming.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

At current rates of carbon dioxide and temperature increase, peatlands are highly likely to release a significant amount of stored soil carbon. Less certain is whether soils in other ecosystems, especially those subject to drought, will respond similarly to elevated temperature.

Summary sentence or paragraph that integrates the above information

The release of carbon from peatland soils could represent a major positive feedback loop to continued disturbance regimes related to climate change and human activities.

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13 Terrestrial Wetlands

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KEY FINDINGS

1. The assessment of terrestrial wetland carbon stocks has improved greatly since the *First State of the Carbon Cycle Report* (CCSP 2007) because of recent national inventories and the development of a U.S. soils database. Terrestrial wetlands in North America encompass an estimated 2.2 million km^2, which constitutes about 37% of the global wetland area, with a soil and vegetation carbon pool of about 161 petagrams of carbon that represents approximately 36% of global wetland carbon stock. Forested wetlands compose 55% of the total terrestrial wetland area, with the vast majority occurring in Canada. Organic soil wetlands or peatlands contain 58% of the total terrestrial wetland area and 80% of the carbon (*high confidence, likely*).

2. North American terrestrial wetlands currently are a carbon dioxide sink of about 123 teragrams of carbon (Tg C) per year, with approximately 53% occurring in forested systems. However, North American terrestrial wetlands are a natural source of methane (CH_4), with mineral soil wetlands emitting 56% of the estimated total of 45 Tg C as CH_4 (CH_4 –C) per year (*medium confidence, likely*).

3. The current rate of terrestrial wetland loss is much less than historical rates (about 0.06% of the wetland area from 2004 to 2009), with restoration and creation nearly offsetting losses of natural wetlands. Although area losses are nearly offset, there is considerable uncertainty about the functional equivalence of disturbed, created, and restored wetlands when comparing them to undisturbed natural wetlands. Correspondingly, there remains considerable uncertainty about the effects of disturbance regimes on carbon stocks and greenhouse gas (GHG) fluxes. For this reason, studies and monitoring systems are needed that compare carbon pools, rates of carbon accumulation, and GHG fluxes across disturbance gradients, including restored and created wetlands. Those studies will produce data that are needed for model applications (*high confidence, likely*).

Note: Confidence levels are provided as appropriate for quantitative, but not qualitative, Key Findings and statements.

13.1 Introduction

The objective of this chapter is to characterize the distribution of carbon stocks and fluxes in terrestrial wetlands within North America. The approach was to synthesize available literature from field measurements with analyses of resource inventory data to estimate wetland area, carbon stocks, and net ecosystem exchange (NEE) of carbon and methane (CH_4) fluxes of terrestrial wetlands (see Appendices 13A, p. 547, and 13B, p. 557, for details[1]). Then, the findings employed from large-scale simulation studies provided additional context, with consideration given to the effects of disturbance regimes, restoration and creation of terrestrial wetlands, and the application of modeling tools to assess the carbon cycle of terrestrial wetlands.

13.1.1 Terrestrial Wetland Definition

This chapter focuses on carbon cycling in nontidal freshwater wetlands (referred to hereafter as "terrestrial wetlands"). Although there are various definitions of terrestrial wetlands (Cowardin et al., 1979; IUSS Working Group WRB 2006), all recognize a high water table level as the driver of biological and chemical processes characteristic of wetlands. The United States defines wetlands as soils that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that do support under normal circumstances, a prevalence of vegetation typically adapted for life in saturated conditions (U.S. EPA 2015). The distribution of U.S. wetlands is considered on the basis of vegetation and hydrogeomorphical setting

[1] The assessment described in this chapter required additional background and parallel analyses of recently published and accessible databases. These analyses pertain only to Ch. 13 and are presented in Appendices 13A and 13B, beginning on p. 547.

using remote-sensing data (Federal Geographic Data Committee 2013). Soils are also indicative of wetland conditions; two major soil types useful for assessing carbon stocks and fluxes recognized here are mineral soils and organic soils. Wetland ecosystems with organic soils, also known as peatlands, are classified as Histosols by the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) Soil Survey (Soil Survey Staff 2010). The Histosol order represents soils with a thick (>40-cm) accumulation of organic matter on top of mineral sediments or rock. Most Histosols are formed under wet conditions (e.g., peat soils), but some of these soils form under aerated conditions. Not considered a wetland, aerated Histosols are distinctly recognized (e.g., suborder Folists) and thus are not considered here. However, all peatlands are formed under wet conditions (Joosten and Clarke 2002), and they are classified as wetlands in Canada (Zoltai and Vitt 1995) and throughout North America (Gorham et al., 2012). The amount and distribution of accumulated soil organic matter reflect the balance between inputs from vegetative production and losses from decomposition or overland transport (e.g., erosion or drainage). While the depth for defining organic soils (Histosols) or peatlands ranges from 10 to 50 cm among different countries, the USDA Soil Survey uses the top 40 cm in the upper 80 cm of soil, which is the definition used here (Soil Survey Staff 2010). Mineral soil wetlands vary widely in the composition and depth of the surface organic layer, varying from a few centimeters to nearly 40 cm in histic-mineral soil wetlands ("histic" refers to soils with a 20- to 40-cm organic horizon, differentiating them from Histosols).

13.1.2 Relationship to Other Chapters and SOCCR1

For this chapter, assessments were made of terrestrial wetlands that occur in boreal, temperate, and tropical climatic zones in Canada, the United States, Mexico, and Puerto Rico. Tidally influenced saltwater and freshwater wetlands are assessed in Ch. 15: Tidal Wetlands and Estuaries, p. 596. Terrestrial wetlands, including peatlands, occurring in the Arctic permafrost zone are assessed in Ch. 11: Arctic and Boreal Carbon, p. 428. Some types of wetlands are transition zones to inland waters (e.g., riparian wetlands). This report considers that inland waters (see Ch. 14: Inland Waters, p. 568) begin at the shoreline of lake, reservoir, and fluvial systems. Both Ch. 9: Forests, p. 365, and this chapter use the definition of forests from the USDA Forest Service's Forest Inventory and Analysis (FIA). As a result, there is overlapping data between Ch. 9 and this chapter. Also, Ch. 10: Grasslands, p. 399, describes wetlands in those domains and thus has some overlapping data with this chapter. Similarly, there are overlapping data with Ch. 12: Soils, p. 469, where organic and mineral soil wetlands are assessed. Since Ch. 5: Agriculture, p. 229, includes no jurisdictional wetlands, it does not have overlapping data.

In the *First State of the Carbon Cycle Report* (SOCCR1; CCSP 2007), the Wetlands chapter (Chapter 13; Bridgham et al., 2007) was inclusive of all terrestrial and tidal wetlands, from tropical to Arctic ecosystems. In the *Second State of the Carbon Cycle Report* (SOCCR2), wetlands are assessed in several chapters as described above.

This chapter adds new information on carbon pools and fluxes from terrestrial wetlands that occur in boreal, temperate, and tropical climate zones within North America. It breaks down carbon pools and fluxes between mineral soil wetlands and peatland ecosystems. It also differentiates carbon pools and fluxes between forested and nonforested wetlands (not done in SOCCR1) because of the influence of trees on ecosystem carbon dynamics (see Figure 13.1, p. 510). The term "flux" is used for carbon dioxide (CO_2) and CH_4 as the net balance between uptake and release of these gases relative to the atmosphere. Finally, this chapter reviews dissolved organic carbon (DOC) fluxes from terrestrial wetlands as well as restored wetlands, but it does not consider constructed wetlands or detention ponds, which typically are engineered systems.

Figure 13.1. Forested Peatland in Northern Minnesota. This bog is part of the U.S. Department of Agriculture (USDA) Forest Services's Marcell Experimental Forest. [Figure source: USDA Forest Service.]

13.2 Current and Historical Context

13.2.1 Wetland Regulations

During the settlement of North America, wetlands were viewed as unproductive areas that were impediments to transportation and development, as well as a breeding ground for disease. That sentiment lasted for over 150 years, during which draining of wetlands for agriculture, forestry, and urban development was routine to make these ecosystems productive for commercial use. Once drained, wetlands generally have very productive soils because of their high organic matter and associated nutrients. Not until the mid-1900s did the effects of wetland drainage on both inherent wetland values and larger landscape impacts begin to be identified. Wetlands are now known to provide critical habitats for many rare species, serve as filters for pollutants and sediment, store water to prevent flooding, and sequester and store carbon, but those ecosystem services were not broadly recognized until relatively recently.

Currently, vegetation removal, surface hardening (e.g., pavement and soil compaction), and drainage are identified as the most common physical stressors on U.S. wetlands (U.S. EPA 2016). To address the threats and subsequent losses of wetlands, wetland policies have been developed to avert further wetland conversion, degradation, or loss. The United States has an overarching policy of "no net loss" of wetlands adopted in 1989. This policy has dramatically slowed U.S. wetland losses and led to the development of wetland banking programs whereby losses due to development are offset by wetlands restored or created elsewhere. In Canada, the main causes for wetland losses are from land conversion to urban or agriculture, water-level control including flooding from hydroelectric development, and climate change (Federal Provincial and Territorial Governments of Canada 2010). In 1991, the Canadian government enacted the Federal Policy on Wetland Conservation (Canadian Wildlife Service 1991). Similarly, the Natural Protected Areas Commission of Mexico announced a national wetland policy in 2014 designed to protect wetlands and avert losses. Recent research in Mexico indicates that drainage for agriculture and conversion to aquaculture are two major threats to wetlands (De Gortari-Ludlow et al., 2015).

These national-level policies are not the only regulations in place designed to protect wetlands. The United States and Canada have wetland-focused state and provincial regulations, as well as other federal regulations that, while not focused on wetlands, do protect wetland habitat. Migratory bird agreements among the United States, Mexico, and Canada often have wetland protection implications. In 1986, the United States and Canada adopted the North American Waterfowl Management Plan and were later joined by Mexico in 1994 (North American Waterfowl Management Plan Committee 2012). This plan establishes strategies to protect wetland habitat for the primary purpose of sustaining migratory bird populations with the associated benefit of protecting carbon pools.

Competing land uses and economic development will continue to threaten wetlands in North America. Multiple policies have been designed to protect against, and mitigate for, wetland loss. However, while losses are greatly stemmed, the United States continues to experience net losses of wetlands in

terms of absolute acreage in spite of the no net-loss policy. Canada and Mexico currently have no nationwide wetlands inventory, limiting the ability to estimate wetland conversion or function, including carbon fluxes and pools. It is important to remember that no net-loss policies do not protect against reduced functionality in restored versus natural wetlands.

13.2.2 Change in Wetland Area

As a result of socioeconomic drivers, there have been massive disturbances and conversions of wetlands over the past 150 or more years in North America. The latest assessment of the status and trends of wetlands in the conterminous United States (CONUS) estimates that there are 445,000 km^2 of wetlands, which includes 395,197 km^2 of terrestrial wetlands (USFWS 2011). In colonial America, there were an estimated 894,000 km^2; between 1870 and 1980, the United States experienced a 53% loss of wetland area (Dahl 1990). From 2004 to 2009, increased wetland restoration on agricultural lands occurred; however, wetland losses continued to outpace gains, leading to a total wetland area decline of 0.06% (USFWS 2011). The current rate of loss is 23 times less than that of the historical trend (e.g., 1870 to 1980), an indication of changing attitudes toward wetlands and the effectiveness of policies to protect them (USFWS 2011).

Although Canada does not have a national wetlands inventory, estimated losses are approximately 14% of the country's original 1,470,000 km^2 of wetlands (Environment Canada 1991). Similarly, an estimated 62% of wetland area has been lost from Mexico's original 112,166 km^2 of wetlands (Casasola 2008; Landgrave and Moreno-Casasola 2012). Mexico's small area of peatlands covers about 20,000 km^2 generally found in high-elevation ecosystems and near-coastal freshwater marshes (Instituto Nacional de Estadística y Geografía 2010). The country has another 15,000 km^2 of mineral soil wetlands.

In CONUS, about 468,000 km^2 of wetlands have been lost, 96% of which have been mineral soil wetlands and 4% peatlands (Bridgham et al., 2007). Similarly, in Canada, of the 212,000 km^2 of wetlands lost, 94% have been mineral soil wetlands and 6% peatlands (Bridgham et al., 2007). However, Canadian peatlands are now being lost in large numbers due to urban development, hydroelectric development, and energy production (Chimner et al., 2016), including in the oil sands region where nearly 300 km^2 have been destroyed by mining (Rooney et al., 2012). In the United States, forested wetlands are undergoing the most rapid losses among terrestrial wetland types. From 2004 to 2009, 1.2% of forested wetlands were lost (2,562 km^2) per year, compared to gains of 1,084 km^2 per year for emergent wetlands and 729 km^2 per year for shrub wetlands (Dahl 2011).

The change in wetland area is quite high in the U.S. Midwest where Iowa, Missouri, Illinois, Ohio, and Indiana have experienced a greater than 85% loss of their wetlands. California has lost 96% of its original wetlands (Dahl 2011; Garone 2011). Other notable ecosystem examples include bottomland hardwood forests of the Lower Mississippi River Alluvial Plain (i.e., southern Illinois to the Gulf of Mexico); these forests, once comprising an area of approximately 85,000 km^2, were reduced to about 20,000 km^2 by 1990, primarily through agricultural conversion and alterations to the hydrological system for flood protection (Stanturf et al., 2000). Major federal flood-control projects that began following a significant flood in 1927 contributed to more than 30% of wetland losses and subsequent agricultural conversions in the Mississippi River Valley (King et al., 2006; Stavins and Jaffe 1990). Similarly, the Prairie Pothole Region (see Section 13.3.3, p. 520) of the United States and Canada included 200,000 km^2 of wetland area prior to European settlement but has since decreased to 70,000 km^2 of intact (i.e., not drained) wetland area (Dahl 2014; Euliss et al., 2006). In contrast, Alaska is reported to have had negligible wetland loss (Bridgham et al., 2007), although the state does not have a completed assessment under the U.S. Fish and Wildlife Service (USFWS) National Wetlands Inventory.

Areal extent alone does not indicate the ecosystem function and services that wetlands deliver. In 2011, the U.S. Environmental Protection Agency (EPA) released the first national assessment of the condition of U.S. wetlands. Findings indicated that 48% of wetlands were in good condition, 20% were in fair condition, and 32% were in poor condition (U.S. EPA 2016). While wetlands may remain intact, their alterations by humans are still affecting the ability of wetlands to function similarly to an unaltered state. Carbon sequestration is one of those important functions affected by wetland condition. Connecting wetland condition to carbon stocks and fluxes will be an important next step for assessing impacts on the carbon cycle.

13.2.3 Overview of Disturbance Effects on Carbon Stocks and Fluxes

Wetlands have been sequestering carbon from the atmosphere for thousands of years. Following the end of the last glacial period about 12,000 years ago, wetlands developed over much of the northern part of North America. Low areas or areas with less permeable soils tended to pond water and create the anoxic environment critical for peatland and mineral soil wetland formation. In undisturbed wetlands, carbon pools are relatively stable over short time intervals, but carbon fluxes may be quite variable due to complex interactions of climate, vegetation, soils, and hydrology. For example, annual CO_2 fluxes ranged from a sink of 2 to 112 grams of carbon (g C) per m^2 per year, and CH_4 fluxes ranged from a source of 2.8 to 4.4 g C per m^2 per year during a 6-year study in a peatland in southern Ontario (Roulet et al., 2007). Carbon dioxide fluxes generally decrease (i.e., sinks or lesser sources) and CH_4 fluxes generally increase (i.e., sources or lesser sinks) as water tables get nearer to the surface (Olson et al., 2013). During droughts or high-water events, CO_2 and CH_4 fluxes can vary greatly, even in undisturbed wetlands. Changes in carbon fluxes resulting from disturbance lead to changes in carbon pools. Drainage is the main human-caused disturbance that has led to a variety of local- to landscape-level impacts. Wetland drainage causes an abrupt change from anaerobic conditions during flooding to aerobic conditions subsequent to drainage, resulting in rapid acceleration of decomposition through microbial oxidation of organic matter (Drexler et al., 2009). As a result, wetland drainage generally leads to lower carbon stocks, lower CH_4 fluxes, and a long-term increase in CO_2 fluxes (Bridgham et al., 2006). In peatlands, drainage also can result in significant land-surface subsidence (Drexler et al., 2009). Other human-caused disturbances include filling of wetlands for development, construction of dams that permanently flood wetlands, stream channelization and road construction that can disconnect wetlands from their water source, removal of vegetation (including forest harvesting), and agricultural conversion of surrounding uplands.

13.3 Current Understanding of Wetland Stocks and Fluxes

The occurrence of the water table within the upper soil layers during the growing season differentiates wetlands from upland ecosystems, influencing the biological communities that must adapt to withstand prolonged periods of soil saturation and biogeochemical processes that are a function of the anoxic soil conditions. While net primary production (NPP) of wetlands is comparable to upland ecosystems (Ahl et al., 2004), the rate of organic matter decomposition is generally less due to the anaerobic soil conditions. As a result, wetland soils typically contain considerably more carbon per unit volume than do upland soils. In areas with prolonged periods of soil saturation and high rates of organic matter production, organic matter may accumulate on top of the mineral substrate, forming organic soils or peatlands with thicknesses ranging from 40 cm to many meters.

The anaerobic conditions of wetland soils also influence greenhouse gas (GHG) fluxes. Unlike upland soils that generally are a sink for atmospheric CH_4, wetland soils typically are a net source of CH_4 to the atmosphere. Methane flux from wetlands is regulated largely by oxygen availability and associated water table position, soil temperature, and vegetation type (Bansal et al., 2016; Green and Baird 2012; Hanson et al., 2016). Hence, fluxes can

be highly variable, even within a wetland, as subtle differences in surface topography, temperature gradients, and vegetation affect fluxes (Bridgham et al., 2006). Accordingly, carbon fluxes and storage in wetlands are likely to change dramatically as a result of climate and land-use changes, which alter water-table dynamics, temperatures, and vegetation communities, ultimately affecting the ecosystem carbon balance. Drainage is the common modification to wetlands for agriculture and silviculture and causes most of the wetland loss noted above. The organic matter decomposition rates of those drained wetlands can be very high, and, for peatlands, the effect may persist for many decades. The soil carbon content of converted wetlands may be greater than the surrounding upland, while the fluxes of GHGs, especially CO_2, are likely larger.

This chapter assessed the state of the wetland carbon cycle, considering organic and mineral soils separately because the soil carbon density, or the amount of carbon per unit volume, varies between the two soil types, and they generally reflect different hydrological settings and vegetation communities. Correspondingly, differentiating between forested and nonforested organic and mineral soil wetlands provides a basis to consider the influence of vegetation on the carbon cycle. The approach for quantifying the wetland carbon pools was based primarily on analyses of recently developed geospatial data, providing a more robust basis for the assessment, as contrasted with summarization based on studies reported in the literature. The general framework, using CONUS as an example, consisted of identifying the distribution of forested and nonforested terrestrial wetlands using the USFWS National Wetlands Inventory. The soil carbon stocks were then determined by summarizing USDA's NRCS Soil Survey databases. Forest vegetation carbon stocks were estimated based on the U.S. Forest Service FIA database (U.S. Forest Service 2003), and nonforest vegetation carbon content was estimated using a mean carbon density based on reported values in the literature. Variations to that framework were necessitated by available databases. For example, in Alaska, where the National Wetlands Inventory has not been completed, a remote sensing–based approach to wetland identification was used (Clewley et al., 2015). Similarly, because Canada does not have a comprehensive national soil inventory, independent assessments of Canadian peatlands and soil landscapes were used. Details about the databases used to calculate the wetland area and associated carbon stocks are provided in Appendix 13A, p. 547.

There are approximately 2.2 million km^2 of terrestrial wetlands in North America (see Table 13.1, p. 514); the majority of those wetlands (81%) occurs in Canada and Alaska. This estimate is approximately 176,000 km^2 less than the one used in SOCCR1 (CCSP 2007). The difference in nonpermafrost peatlands and freshwater mineral soil wetlands among the two reports is due primarily to a smaller and more accurate and current assessment of wetland area in Alaska (Clewley et al., 2015), which reduced the total wetlands in the state by approximately 360,000 km^2; Canadian wetlands increased by approximately 198,000 km^2 due primarily to a larger estimate of mineral soil wetlands. The uncertainty in wetland area is greatest at the higher latitudes, hence the reliance on remote-sensing methods for spatial extent estimates, which are expected to improve further as data and processing tools advance. The report on Alaskan wetlands by Clewley et al. (2015) is an example of achieving an accuracy of approximately 94% in discriminating wetlands from uplands. There remains uncertainty in the reported area of Canadian peatlands, which ranges from the 755,000 km^2 reported by Kroetsch et al. (2011) to the 1.1 million km^2 reported in SOCCR1 (Bridgham et al., 2007). In contrast to reported inventories and assessments used in SOCCR1, Zhang et al. (2017a) used six models to estimate wetland area for North America (including coastal wetlands), with the modeled estimates ranging from about 1.1 to 3.3 million km^2, effectively placing the estimated total in Table 13.1 in the middle of that range. Correspondingly, there are large ranges in estimated global wetland area. Based on modeled and observational estimates (Bridgham et al., 2006; Melton et al., 2013; Zhang et al., 2017a), North

Table 13.1. Area, Carbon Pool, Net Ecosystem Exchange of Carbon, and Methane Emissions from Wetlands in North America[a–c]

Wetland Type	Area[d] (km^2)	Carbon Pool[e] (Pg C)	NEE[f]	CH_4 Emissions	
			Net Balance (Tg C per Year)[g]	CH_4-C (Tg C per Year)[g]	CH_4 (Tg per Year)
Canada					
Peatland					
Nonforested	415,450	37.8	–6.9 ± 3.5	9.4 ± 2.4	12.6
Forested	703,785	76.7	–33.6 ± 5.9	6.3 ± 7.4	8.4
Mineral					
Nonforested	103,932	9.5	–10.6 ± 7.2	2.7 ± 0.7	3.6
Forested	268,337	5.1	–12.9 ± 6.8	7.2 ± 4.3	9.6
Total	1,491,504	129.0	–64.0 ± 12.0	25.6 ± 8.9	34.2
Conterminous United States					
Peatland					
Nonforested	42,903	3.9	–5.8 ± 3.6	1.0 ± 0.3	1.3
Forested	40,823	4.4	–4.9 ± 3.8	0.4 ± 0.4	0.5
Mineral Soil					
Nonforested	138,381	1.9	–14.1 ± 9.5	3.6 ± 1.0	4.8
Forested	173,091	3.3	–11.6 ± 8.2	4.7 ± 2.8	6.2
Total	395,197	13.5	–36.5 ± 13.6	9.6 ± 3.0	12.8
Alaska					
Peatland					
Nonforested	73,836	5.5	–4.2 ± 4.7	1.7 ± 0.4	2.2
Forested	5,747	0.4	–0.3 ± 0.4	0.1 ± 0.1	0.2
Mineral Soil					
Nonforested	192,013	9.3	–10.9 ± 12.3	5.0 ± 1.4	6.7
Forested	40,162	2.0	–2.3 ± 2.6	1.1 ± 0.6	1.4
Total	311,758	17.3	–17.6 ± 13.5	7.9 ± 1.6	10.5
Puerto Rico					
Peatland					
Nonforested	8	0.001	–0.003 ± 0.003	3.38E-04[h] ± 2.88E-04	0.0
Forested	1	0.000	0.000 ± 0.000	2.68E-05 ± 2.28E-05	0.0
Mineral Soil					
Nonforested	252	0.006	–0.030 ± 0.110	1.36E-02 ± 0.488E-02	0.0
Forested	50	0.001	–0.006 ± 0.022	2.70E-03 ± 0.966E-03	0.0
Total	311	0.008	–0.039 ± 0.110	1.67E-02 ± 0.500E-02	2.22E-02
Mexico					
Peatland					
Nonforested	17,191	0.43	–5.33 ± 5.25	0.69 ± 0.59	0.9
Forested	3,394	0.24	–1.05 ± 1.04	0.14 ± 0.12	0.2

Continued on next page

(Continued)

Table 13.1. Area, Carbon Pool, Net Ecosystem Exchange of Carbon, and Methane Emissions from Wetlands in North America[a–c]

Wetland Type	Area[d] (km^2)	Carbon Pool[e] (Pg C)	NEE[f]	CH_4 Emissions	
			Net Balance (Tg C per Year)[g]	CH_4-C (Tg C per Year)[g]	CH_4 (Tg per Year)
Mexico (continued)					
Mineral Soil					
Nonforested	10,320	0.35	–1.25 ± 4.51	0.56 ± 0.20	0.7
Forested	5,288	0.16	–0.64 ± 2.31	0.29 ± 0.10	0.4
Total	36,193	1.17	–8.27 ± 7.37	1.67 ± 0.640	2.22
North America					
Peatland					
Nonforested	549,388	47.7	–22.2 ± 17.1	12.8 ± 3.7	17.0
Forested	753,749	81.8	–39.9 ± 11.0	6.9 ± 8.0	9.2
Mineral Soil					
Nonforested	444,898	21.1	–36.9 ± 33.6	11.9 ± 3.3	15.9
Forested	486,928	10.4	–27.4 ± 19.9	13.3 ± 7.8	17.7
Total	2,234,963	161.0	–126.4 ± 23.8	44.8 ± 9.5	59.8

Notes

a) Positive emissions indicate net gains to the atmosphere, and negative emissions indicate net gains or sequestration into the ecosystem.

b) Citations and assumptions in calculations are in the text of this chapter and in Appendices 13A, p. 547, and 13B, p. 557.

c) Key: C, carbon; NEE, net ecosystem exchange; CH_4, methane; Pg C, petagrams of carbon; Tg C, teragrams of carbon.

d) Includes freshwater and nontidal terrestrial wetlands. Accuracy of wetland area estimates: Canada: >66% (Tarnocai 2009), conterminous United States: >90% (Nichols 1994), Alaska: 95% (Clewley et al., 2015), Puerto Rico: >90% (Nichols 1994), Mexico: <75% (this report); see Appendix 13A, p. 547, for more information.

e) Includes soil and plant carbon; soil carbon accounts for approximately 93% of the total pool.

f) Includes net exchange of CO_2 from the wetland; it does not include lateral fluxes or CH_4 fluxes.

g) The values here are mean values plus or minus 2 times the standard errors to approximate the minimum and maximum values of a 95% confidence interval.

h) E = 10x.

America contains 20% to 47% of the global wetland area, depending on the basis.

The dominant carbon flux from terrestrial wetlands is characterized as NEE of CO_2, which is a measure of the difference in CO_2 uptake and CO_2 release; NEE is positive when the net flux is from the wetland to the atmosphere. In addition to NEE of CO_2, this chapter also reports CH_4 fluxes from the wetlands. Estimates of these fluxes are based on studies reported in SOCCR1 (CCSP 2007) and subsequent literature that used field-based measurements to estimate NEE and CH_4 fluxes (either chamber based or eddy covariance). This chapter categorizes the studies by soil, vegetation type, and region and utilizes a mean flux as the basis for the flux density (flux per unit area) used in the reported regions (see Appendix 13B, p. 557, for flux density factors used in the analyses). Though NEE and CH_4 fluxes are the primary fluxes considered, the wetland net ecosystem carbon balance (Chapin et al., 2006), which is the overall net change in wetland carbon

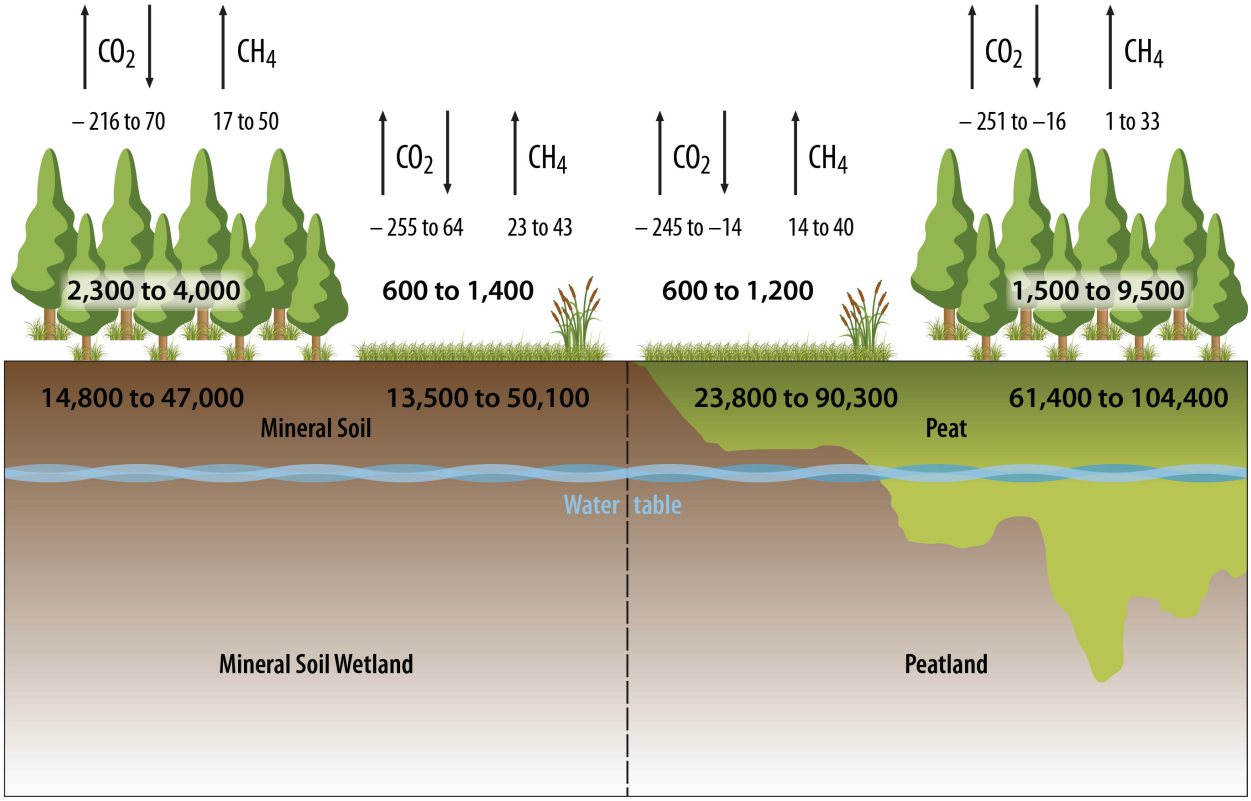

Figure 13.2. Carbon Pools and Fluxes in Forested and Nonforested Mineral Soil Wetlands and Peatlands in North America. The soil and vegetation carbon pools are represented by the range of carbon densities (minimum to maximum) among Canada, Mexico, and the United States. Annual carbon dioxide (CO_2) and methane (CH_4) fluxes (arrows) are represented by a 95% confidence interval; a negative flux indicates a transfer of carbon from the atmosphere to the ecosystem. Stocks and fluxes are in grams of carbon (g C) per m^2. [Data sources: Table 13.1, p. 514, and Appendices 13A and 13B, p. 547 and p. 557, respectively.]

over a specified time, is also influenced by other fluxes. These additional fluxes include carbon monoxide and volatile organic carbon to the atmosphere (e.g., from fires), lateral fluxes of DOC (see Section 13.3.3, p. 520), dissolved inorganic carbon (DIC), and particulate carbon (Chapin et al., 2006).

Peatlands tend to store more soil carbon than mineral soil wetlands, and forested wetlands store more carbon in the vegetation than nonforested wetlands (see Figure 13.2, this page). Across all studies used in this chapter's analysis, fluxes of CO_2 are overlapping across all wetland types but both forested and nonforested mineral soil wetlands tend to be larger sources (or lesser sinks) of CO_2 (see Figure 13.2). Similarly, CH_4 fluxes overlap across all wetland types, yet all wetland types tend to be sources of CH_4 (see Figure 13.2, this page).

13.3.1 Peatlands—Carbon Stocks and Fluxes

Peatlands include those ecosystems with organic soils generally classified as either fens or bogs, both of which are defined by water source and pH. Fens tend to be fed by groundwater and precipitation and have circumneutral pH values with vegetation generally dominated by sedges (*Carex* spp.) and brown mosses. In contrast, bogs are predominantly precipitation fed and have much lower pH and *Sphagnum* mosses. Other types of peatlands include riparian systems such as bottomland hardwood ecosystems

in the Mississippi River Valley, pocosins, Atlantic white cedar swamps, Carolina bays in the southeastern United States, and high-elevation peatlands in the Rocky Mountains from Canada to Mexico and throughout the Sierra Nevada of California. The total area of peatland in North America is about 1.3 million km^2 (see Table 13.1, p. 514).

Peatlands contain about 80% of the wetland carbon stock in North America and account for 48% of the net annual carbon uptake and 44% of the annual CH_4 flux. Approximately 58% of peatlands in North America are forested. The peatland carbon pool in Canada is currently estimated at 114 petagrams of carbon (Pg C), about 67% of which occurs in forests. This pool represents 88% of the total peatland carbon stock for North America (see Table 13.1, p. 514). Canadian peatlands have an estimated annual uptake of 41 teragrams of carbon (Tg C) and an estimated release of 16 Tg CH_4-C per year, 61% from nonforested peatlands. Alaska contains 42% of the U.S. peatland carbon stock and accounts for approximately 39% of the carbon uptake. Forests compose 49% of the peatland carbon stock in CONUS and 7% in Alaska. Methane from U.S. peatlands is 7% of the North American annual peatland flux; CONUS contributes 43% of the U.S. CH_4 flux. This difference in stocks and fluxes between the two countries having the majority of North American peatlands is attributable to the much larger peatland area in Canada. Mexico contains the largest area of tropical peatlands (~20,600 km^2), which constitutes approximately 57% of the total wetland area of the country (see Table 13.1, p. 514). Those peatlands contribute 2% of the North American peatland CH_4 flux as a result of the high flux rates in the tropics. Additionally, small areas of tropical peatlands occur in Puerto Rico (9 km^2). The estimated CH_4 emission is quite variable for each country or state, with the 95% confidence interval varying from 26% to 118% and 85% to 269% of the mean for temperate and tropical wetlands (see Table 13.1, p. 514), which is a reflection of the high degree of variability in the reported measurement data. The CH_4 fluxes applied for forested and nonforested peatlands (8.9 and 22.7 g C per m^2 per year, respectively) are less than the 26 g C per m^2 per year average for bogs and fens reported by Turetsky et al. (2014).

There is wide variation in intrinsic peat properties that influences the carbon stored in peat and how fast it accumulates after disturbances or with succession. Peat properties related to carbon storage are directly linked to the source material that changes with peatland type (Kracht and Gleixner 2000; Schellekens et al., 2012). For example, "peat moss," or *Sphagnum*-derived peat, is different in soil carbon density than peat derived from woody plants ("silvic peat"). Also, peat decomposition rates tend to increase with decreases in water tables (Ise et al., 2008). As such, care is needed in making broad assessments of peat accumulation in forested versus open peatlands, especially since dominant cover types can change (e.g., from silvic peat to *Sphagnum* peat) over time, and water tables can be influenced by short- and long-term precipitation patterns (e.g., droughts) and anthropogenic disturbances (e.g., draining). These factors all contribute to the large amount of variation in peatland carbon cycling and rates of peat accumulation. Peat carbon accumulation rates since the last glaciation range from 7 to 300 g C per m^2 per year (Kolka et al., 2011) in North America, with an average of 23 g C per m^2 per year during the Holocene (Loisel et al., 2014), but values commonly range from 20 to 30 g C per m^2 per year (Manies et al., 2016). In terms of peat accumulation, long-term rates range from 0.2 to 10 mm per year but typically range from 0.4 to 2.0 mm per year across all North American peatland types (Kolka et al., 2011). Peatland carbon pools are dependent on the depth of peat, ranging from 20,000 g C per m^2 in shallow peatlands to more than 300,000 g C per m^2 in peatlands >5 m deep (Kolka et al., 2011).

Generally, any factor that lowers the water table relative to the peat surface will result in increased CO_2 production, increased decomposition, and decreased CH_4 production (Waddington et al., 2015). There are also generalizations that can be made across peatland types, although variation in CO_2 and CH_4 production is high (e.g., McLaughlin and Webster

2014). Fen ecosystems are generally characterized by having relatively low CH_4:CO_2 fluxes compared with systems having very little water movement such as bogs, though fluxes vary greatly, both seasonally and latitudinally. In northern peatlands, CH_4 fluxes are generally highest when water tables are near the peat surface and seasonal temperatures are high (Turetsky et al., 2014). Pocosin ecosystem soils are in contact with groundwater except during seasonal droughts, thus their gaseous fluxes can be variable but generally produce less CH_4 than northern peatlands (Bridgham and Richardson 1992). The reduced gaseous fluxes of pocosins may be related to the high polyphenol content of their peats that resists decomposition even during moderate drought (Wang et al., 2015). The composition of the organic matter in peatlands also affects fluxes of CH_4 and CO_2, with low-quality peat maintaining low rates of decomposition, even when aerated (see Figure 13.3, this page). Those effects are evident both within and between climatic zones.

Gaps in research and monitoring activities to better understand how peatland carbon storage may change in an altered future climate are related mainly to disturbance events that dramatically alter the mechanisms of peat carbon accumulation and stability. Disturbance events of concern are those that alter wetland hydrology, which has a direct feedback to primary production and decomposition. While there is well-developed literature demonstrating that lower water tables coincident with changing precipitation patterns or altered drainage often result in a decline in the carbon sink strength of northern peatlands (Waddington et al., 2015), altered hydrology also has been shown to increase the vulnerability of northern latitude peatlands to wildfire (Benscoter et al., 2011; Turetsky et al., 2011a; Waddington et al., 2012), hence further increasing the vulnerability of peatland carbon pools to decomposition. Research has demonstrated that the extent of fires in boreal North America has steadily increased over the past five decades (Kasischke and Turetsky 2006), often with substantial peat combustion (Turetsky et al., 2011b). For example, a single fire event in northern peatlands can consume 3.3 to

Figure 13.3. Organic Soil Peat Core. Composed primarily from partially decomposed organic matter, this peat sample is from Drosera Fen in Yosemite National Park. [Figure source: Judith Drexler, U.S. Geological Survey.]

3.6 kg C per m^2 (Reddy et al., 2015; Turetsky et al., 2011b), recovery from which would require about 140 years. Disturbance-mediated changes in vegetation community composition also have implications for gas production because different plant species functionally alter rates of CO_2 and CH_4 fluxes from peat, or they affect the ability of peat to resist decomposition (Armstrong et al., 2015; Turetsky et al., 2014). Taken together, the effects of altered hydrology (whether induced by management or as a climatic response) on fire regime and productivity and changes in plant species composition represent key uncertainties in the current understanding of peatland carbon storage in an altered future climate.

13.3.2 Mineral Soil Wetlands—Carbon Stock and Fluxes

The total area of mineral soil wetlands in North America is about 0.9 million km^2 (see Table 13.1, p. 514). The United States contains 52% of the mineral soil wetland carbon stock in North America. Mineral soil wetlands in CONUS have an estimated carbon stock of 5.2 Pg C, with a net annual sequestration of 25.7 Tg C as CO_2 (Tg CO_2-C) and an estimated emission of 8.3 Tg CH_4-C per year (see Table 13.1). Alaska has a larger stock (11.3 Pg C), annual sequestration as CO_2 (13.2 Tg C), and CH_4

release (6.1 Tg CH_4-C). Canadian mineral soil wetlands have a carbon stock of 14.6 Pg C, with an annual CO_2 uptake of 23.5 Tg C and an estimated release of 9.9 Tg CH_4-C per year (see Table 13.1). Mexico has much smaller mineral soil wetland stock (0.5 Pg C), CO_2 sequestration, and CH_4 emissions. The estimates of the exchange of CO_2-C and CH_4-C are quite variable, with the 95% confidence interval ranging from 18% to 360% of the reported mean. Mineral soil wetland carbon stocks in North America are nearly equally divided between nonforested and forested wetlands, 48% and 52%, respectively. Methane releases from the wetlands are greatest for mineral soil wetlands in Canada, followed by CONUS and Alaska (see Table 13.1, p. 514); these estimates also are variable, having a 95% confidence interval ranging from 28% to 61% of the reported mean.

Different national agencies classify mineral soil wetlands differently, using various terms such as marshes, swamps, riverine wetlands, palustrine wetlands, prairie potholes, playas, and Carolina bays, as well as many other local and regional terms. Geography and geomorphology are distinguishing factors in some classifications and influence carbon dynamics. Although there is value in broad classifications, such as forested versus nonforested as in Table 13.1, it is important to recognize that boreal, temperate, and tropical regions in North America span from just over 14°N latitude along the Mexican border with Guatemala to boreal regions of Alaska and Canada positioned to 60° to 70°N latitude. Variation in the carbon pool within these mineral soil wetland types and regions correlates strongly with latitude. Modeled NPP of wetlands across all types, including organic soil wetlands, ranged from 461 to 618 g C per m^2 per year for tropical and lower-latitude temperate regions to as little as 172 to 183 g C per m^2 per year in boreal regions (Cao et al., 1996). Summarizing carbon dynamics in tropical wetlands, Sjogersten et al. (2014) reported an average NPP of 880 g C per m^2 per year for tropical mineral soil wetlands. The proportion of carbon being returned to the atmosphere as CH_4 also decreased with increasing latitude, with CH_4 fluxes varying slightly with respect to whether wetlands were forested or nonforested along this latitudinal gradient (see Table 13.1, p. 514). The data reported by Cao et al. (1996) do not differentiate organic soil wetlands from mineral soil wetlands, but reductions in NPP and CH_4 fluxes for mineral soil wetlands are included and would track with these overall patterns.

Mineral soil wetland carbon pools include those with soil organic layers that are less than 40 cm thick. The Intergovernmental Panel on Climate Change (IPCC) considers a soil depth down to 30 cm as the lower limit for reporting of mineral soil wetland carbon pools (IPCC 2013). To a depth of 30 cm, carbon pools range from 2,200 g C per m^2 in dry tropical mineral soil wetlands to greater than 10,000 g C per m^2 in boreal and moist temperate wetlands (Batjes 2011; Wickland et al., 2014). U.S. soil surveys consider soil properties in the upper 200 cm, but values in the top 150 cm are reported in this chapter to provide a uniform basis of comparison that includes both the surface soil layers and the subsoil.

Seasonal and diurnal fluxes of GHGs from boreal and temperate mineral soil wetlands have a wide range. For example, from temperate forested wetlands, CO_2 fluxes ranged from –0.444 to 3.303 g C per m^2 per day and CH_4 fluxes ranged from –0.014 to 0.0199 g C per m^2 per day (Alford et al., 1997; Harriss and Sebacher 1981; Harriss et al., 1982, 1988; Kelley et al., 1995; Krauss and Whitbeck 2012; Miller and Ghiors 1999; Mulholland 1981; Pulliam 1993; Wilson et al., 1989; Yu et al., 2008). The fluxes depend on the wetland type, soil temperature, and soil water regime. These factors are affected not only by latitude, but also by land-use change, leading to much assessment difficulty and uncertainty. North American wetlands release approximately 44 Tg CH_4-C per year, but the uncertainty surrounding this value is considerable (see Table 13.1, p. 514). For nonforested mineral soil wetlands of North America, NEE of carbon as CO_2, ranged from an average of –264 to 527 g C per m^2 per year. Methane was emitted from these same wetlands at rates of 0.8 to 127 g C per m^2 per year. Such broad ranges of CO_2 and CH_4 fluxes reflect

sensitivity to biotic and abiotic factors, which drive high uncertainty in estimating the net carbon balance and changes in carbon sinks at large scales and time periods.

Understanding the carbon balance across gradients of hydrology and vegetation within a mineral soil wetland is crucial to determining landscape-scale fluxes, especially for systems associated with fluvial networks. For instance, in a short-hydroperiod floodplain wetland in Virginia, GHG fluxes varied dramatically depending on the floodplain geomorphic unit (i.e., levee, backswamp, and toe slope) and in relation to longitudinal position (i.e., upstream versus downstream; Batson et al., 2015). The focus is often on the *in situ* capacity of forested mineral soil wetlands in controlling the carbon balance. However, many forested mineral soil wetlands are positioned for *allochthonous* inputs, (i.e., organic and inorganic carbon [including dissolved CO_2] that moves across terrestrial landscapes to aquatic environments). Such inputs, along with erosion, may influence the carbon balance significantly through external drivers (Ensign et al., 2013; Noe et al., 2016). Data on these inputs are few, as research has focused intently over the past several decades on carbon balance from organic soil wetlands (e.g., fens, bogs, and coastal marshes).

Prairie "potholes" represent one type of mineral soil wetland that has been studied intensively. The Prairie Pothole Region (PPR) is home to the largest inland mineral soil wetland ecosystem in North America. Covering about 777,000 km^2 of north-central United States and south-central Canada, the PPR is characterized by millions of closed depressional, mineral soil wetlands or potholes encompassing approximately 70,000 km^2 of undrained wetlands (Dahl 2014; Euliss et al., 2006). The distinguishing feature of prairie potholes is their lack of a discernable surface drainage network. These wetlands have the potential to represent a considerable contribution to the North American GHG balance, both as carbon storage and sequestration sites and as sources of GHGs (Badiou et al., 2011; Bansal et al., 2016; Tangen et al., 2015). PPR wetlands, also characterized by periods of inundation ranging from ephemeral to permanent, exist along a water-salinity gradient from fresh to hypersaline and occur primarily within a matrix of croplands and grasslands (Euliss et al., 2004; Goldhaber et al., 2014; Niemuth et al., 2010; Winter and Rosenberry 1998). Many PPR wetlands contain sulfate concentrations comparable to coastal systems, resulting in inhibition of CH_4 production (Goldhaber et al., 2014). Consequently, the biotic and abiotic factors that regulate the carbon dynamics and GHG balance of these systems are highly variable, both temporally and spatially.

Previous work recognizing PPR wetlands as significant carbon storage sites (Euliss et al., 2006) and identifying mineral soil wetlands as a major data gap (Bridgham et al., 2006, 2007) spurred considerable research in recent years pertaining to the overall GHG balance of these wetlands. Soil carbon stores are reduced by 12% to 26% when wetlands are converted from native grasslands to agricultural uses, presumably due to wetland drainage and soil disturbance (Gleason et al., 2008, 2009; Tangen et al., 2015). Peak CH_4 fluxes can exceed 0.75 g C per m^2 per day, and maximum cumulative seasonal CH_4 fluxes have been shown to be among the greatest reported for North American wetlands (Bansal et al., 2016; Bridgham et al., 2006; Tangen et al., 2015). In terms of the overall radiative balance of PPR mineral soil wetlands, CO_2 contributes the most (about 90%) to net GHG flux, followed by CH_4 (about 9%) and N_2O (about 1%; Gleason et al., 2009).

13.3.3 Lateral Carbon Fluxes from Terrestrial Wetlands

The lateral flux of carbon may occur in the form of DIC, DOC, dissolved CH_4, and particulates. The DOC flux is generally the largest of these fluxes from wetlands and is particularly important because it can be a source of carbon to both surface and groundwater. The rates of DOC production and loss are variable across time, space, and wetland types and appear to be climate dependent (Drösler et al., 2014). The transport of DOC to surface waters is fairly well studied for peatlands (Hope et al., 1994).

The IPCC Wetlands Supplement (2013) chapter on drained inland organic soils reviewed the literature and estimated DOC flux from natural systems across biomes. As part of that supplement, Drösler et al. (2014) found 1) boreal peatland flux to surface waters to be 8.4 g C per m^2 per year (95% confidence interval ranging from 6.0 to 11.1 g C per m^2 per year), 2) temperate peatland flux to surface waters to be 21.2 g C per m^2 per year (17.3 to 26.2 g C per m^2 per year), and 3) tropical DOC fluxes to surface waters to be 56.9 g C per m^2 per year (49.2 to 63.8 g C per m^2 per year). Higher temperatures lead both to more production and decomposition and to higher DOC fluxes.

However, mineral soil wetlands are not well studied, possibly because many mineral soil wetlands have no surface stream drainage outlet. Studies conducted in the temperate northeastern United States summarized data for 30 forested watersheds with no wetlands present and found DOC fluxes to range from 0.5 to 4.9 g C per m^2 per year (mean = 2.4 g C per m^2 per year; Raymond and Saiers 2010), considerably lower than the aforementioned mean of 21.2 g C per m^2 per year found for peatlands. At least for the temperate zone, these fluxes can be considered as the lower bound of mineral soil wetland fluxes. Aitkenhead and McDowell (2000) reviewed the literature and compared riverine DOC fluxes across a wide range of climate and vegetation biomes but did not differentiate DOC contributions between peatland and mineral soil wetlands. Here, the studies in known mountainous and peatland watersheds were removed, with the caveat that they are stream and river fluxes, not wetland fluxes. This chapter estimated the mean DOC flux for streams and rivers that have considerable mineral soil wetlands in their watersheds. The mean DOC flux for mineral soil wetlands in 1) tropical systems is estimated as 9.9 g C per m^2 per year (n = 2; Day et al., 1977; Malcolm and Durum 1976); 2) in temperate systems, as 5.4 g C per m^2 per year (n = 6; Clair et al., 1994); and 3) in boreal systems, as 2.1 g C per m^2 per year (n = 16; Clair and Ehrman 1996; Mulholland and Watts 1982).

Interestingly, this chapter's estimates of mineral soil wetland DOC fluxes as a percentage of organic soil DOC fluxes are relatively consistent across the three biomes (25%, 25%, and 17%, respectively, for boreal, temperate, and tropical ecosystems). DOC fluxes from North American terrestrial wetlands can be estimated using the wetland areas in Table 13.1, p. 514, and characterizing Alaska and Canada as boreal, CONUS as temperate, and Puerto Rico and Mexico as tropical. Boreal DOC fluxes are 11.4 Tg (10.1 Tg from organic wetland soils and 1.3 Tg from mineral wetland soils). Temperate DOC fluxes are 3.5 Tg (1.8 Tg from organic wetland soils and 1.7 Tg from mineral wetland soils). Tropical DOC fluxes are 1.4 Tg (1.2 Tg from organic wetland soils and 0.2 Tg from mineral wetland soils). Together, these fluxes total 16.3 Tg DOC for North America. Although there is low confidence in the amount of lateral DOC fluxes, especially those related to mineral soil wetlands, these fluxes are lower but of similar magnitude as the NEE and about 37% of the CH_4 fluxes from terrestrial wetlands (see Table 13.1).

13.3.4 Carbon Stock and Balance

The estimated North American terrestrial wetland carbon pool of 161 Pg C is less than the 214 Pg C reported in SOCCR1 for permafrost peatlands, nonpermafrost peatlands, and freshwater mineral soil wetlands (CCSP 2007). This difference is attributable to the inclusion of permafrost wetlands in the SOCCR1 report (CCSP 2007) and differences in nonpermafrost wetland area. The estimate here (129 Pg) for the amount of carbon stored in North American peatlands is less than that (163 Pg) reported by Gorham et al. (2012), again, likely a result of the Arctic permafrost area.

The development of a carbon balance sheet for the terrestrial wetlands of North America provides a useful perspective for considering the relative contributions of the various pathways, the relative differences in fluxes, and uncertainties. The wetland carbon balance sheet can be simplified by considering NEE as the net change in the CO_2-carbon exchange between the wetland and the atmosphere (negative values indicate net transfer to

the ecosystem). Net gains to the wetland, assuming a negative NEE, are effectively allocated among vegetation and soils. The principal losses of carbon from the wetlands that are not included in NEE are CH_4 fluxes (see Sections 13.3.1, p. 516, and 13.3.2, p. 518), DOC (see Section 13.3.3, p. 520), hydrological fluxes of DIC and suspended particulates, and losses due to episodic disturbance regimes (e.g., fire). Unfortunately, there is very little information about the loss of carbon as DIC or particulates for terrestrial wetlands. Thus, for current purposes, they are not considered further. Accordingly, the net ecosystem carbon balance for terrestrial wetlands in North America is –65.3 Tg C (–126.4 Tg C input, see Table 13.1, + 44.8 Tg CH_4-C flux, see Table 13.1, + 16.3 Tg DOC loss, see Section 13.3.3), indicating that the wetlands are a net carbon sink. However, the estimated annual accumulation in carbon among the soil and vegetation pools, 47.9 and 43.6 Tg C per year, respectively, yields an imbalance of +30 Tg C, indicating that the estimated NEE is too low or that one or more of the components are overestimated.

There is considerable variability in estimates of wetland carbon fluxes, whether it is from field measurements or large-scale simulations. Accordingly, comparison among reports provides useful perspectives. The North American terrestrial wetland CH_4 flux, based on measurements and extrapolated to the wetland area, is estimated at 45 Tg C per year, which is considerably higher than the estimated amount in SOCCR1 (6.1 Tg C per year). SOCCR1 also used measurements as the basis (CCSP 2007); however, the SOCCR2 estimate is nearer the range of several recent modeling studies. Using an ensemble of models to simulate CH_4 emissions in North America, Poulter et al. (2017) reported annual emissions of 31.8 to 33.5 Tg C for 2007 to 2012. Similarly, using six different datasets, Zhang et al. (2017a) reported an average CH_4 emission rate of 22.6 Tg C per year for the region from 2000 to 2006. This amount is similar to the average annual emission estimated for 1979 to 2008 of 17.8 Tg C per year by Tian et al. (2010). The annual global CH_4 flux from wetlands is estimated between 124 and 139 Tg C per year (Saunois et al., 2016; Bloom et al., 2017; Poulter et al., 2017; Zhang et al., 2017a, b); accordingly, the contribution of North America to the global CH_4 budget is likely within the range of 20% to 30%. While there are not any large-scale NEE assessments, synthesizing measurement data for terrestrial wetlands, Lu et al. (2017) report an average annual accumulation rate of 93 g C per m^2, which is considerably higher than the average rate of 53 g C per m^2 reported here.

Assessing the pools associated with the carbon balance sheet provides additional perspective. Both organic and mineral soils accumulate carbon. Estimates here of carbon accumulation in the soil are 25 and 17 g C per m^2 per year for peat and mineral soils, respectively; those aggregated rates are based on the mean accumulation rates, reported by Bridgham et al. (2006), weighed by the wetland area. Accordingly, peat and mineral soils gain approximately 32.2 and 15.9 Tg C per year, respectively. Although there is a wide range in vegetation productivity, an estimated 43.6 Tg C is sequestered in biomass annually. The estimate assumes that accumulation in plant biomass is balanced with decomposition in nonforested wetlands and that forested wetlands have a net accumulation of 30 to 50 g C per m^2 per year (Bridgham et al., 2006; Stinson et al., 2011). The resulting summation of carbon sequestration by the soil and vegetation components (92 Tg C) is greater than the allocation to CH_4 fluxes or DOC.

13.4 Wetland Management, Restoration, and Creation

Generally, terrestrial wetlands are managed for one or more of the ecosystem services they provide. In many cases, wetlands are managed as set-aside areas used as natural filters for water quality, areas for rare species, and land for hunting and trapping due to their faunal diversity. For example, several international conservation organizations consider the PPR of the midwestern United States and Canada as the most important waterfowl habitat in North America. Management decisions and development that change the hydrology, soils, or vegetation will

affect carbon dynamics, often leading to enhanced decomposition, decreased CH_4 flux, and reduced carbon sequestration, particularly when wetlands are drained. In contrast, restoration of drained wetlands (or avoided loss of wetlands through easements) increases carbon sequestration and CH_4 production. Policies using wetlands as carbon banks and using the carbon gained through wetland restoration to trade in carbon markets are becoming increasingly common globally.

13.4.1 Effects of Wetland Management, Restoration, and Creation on Carbon

This section considers wetland management that does not convert wetlands to another land use. Wetland management occurs on a gradient from very intensive management to preservation. As they have been for thousands of years, wetlands managed for preservation or their intrinsic ecosystem services generally are carbon sinks, although there are some indications that rising temperatures from climate change may be changing wetlands from sinks to sources. For example, an undisturbed bog in Canada was a carbon source for 3 years of a 6-year study (Roulet et al., 2007). Even if wetland sinks are smaller than they once were, management or restoration practices could have dramatic feedbacks to atmospheric concentrations of CO_2 and CH_4. In a management example, there are approximately 658 km^2 of terrestrial wetlands under "moist-soil" management in the U.S. National Wildlife Refuge System, where lands are flooded for wintering and migrating waterfowl. Research has demonstrated that seasonal drainage in moist soil regimes leads to major losses of soil carbon (Drexler et al., 2013). The practice of deeply flooding marshes is not as common in the national wildlife refuges as seasonal drainage, but deep flooding may be an option for increasing carbon sequestration rates (Bryant and Chabreck 1998).

The effect of altered hydrology does not necessarily cause a loss of ecosystem carbon from managed wetlands. Studies of carbon pool response to managed peatlands in Finland have shown that increased forest productivity may offset losses due to water management resulting in a net increase of carbon, but this response is site dependent (Minkkinen et al., 2008). Similarly, forest harvesting only had a transient effect on the soil carbon pool of a mineral soil wetland (Trettin et al., 2011). In contrast, peat utilization, as in peat mining for fuel or horticultural purposes, is the extreme where the peat itself is removed from the wetland. Although peat mining is not common in North America, Canada is the third largest producer of horticultural peat in the world, with much of the peat originating from the peatlands in the St. Lawrence Lowlands on the Canadian side of the Great Lakes (Van Seters and Price 2001). For production agriculture where wetlands remain wetlands, water levels are typically controlled to maximize production, usually at the expense of carbon pools. Prairie potholes and other hydrologically isolated wetlands are often nested within agricultural lands but remain undrained. These cropped, undrained wetlands can be major sources of GHGs due to increased nutrient loading and associated nitrous oxide (N_2O) fluxes. In addition, temporarily ponded wetlands that dry down during the growing season can be tilled and farmed, increasing decomposition rates. Approximately 6,500 km^2 of U.S. peatlands are being used for crop production (ICF International 2013). The converted peatlands are usually highly productive for agriculture, but they also have high potential as GHG mitigation sites if the land is restored to vegetated wetlands (Richardson et al., 2014; Wang et al., 2015). Specific GHG mitigation benefits accrue from 1) decreases in CO_2 fluxes related to the oxidation of soil carbon while in crop production, 2) decreases in the use of nitrogen fertilizers, 3) decreases in lime application amendments, and 4) increases in carbon sequestered in soils and perennial vegetation (ICF International 2013). Crops such as sugarcane lead to large losses of carbon through enhanced decomposition (Baker et al., 2007). Paddy rice production systems are well-known sources of CH_4 (Lindau et al., 1993) and N_2O. Other crops such as sugar beet, radish, cranberry, blueberry, lettuce, celery, carrot, potato, onion, and mint are grown in wetlands, but little data exist on their influence on ecosystem carbon balance.

Similarly, aquaculture has altered wetlands in North America, but, again, little data exist on the impact on carbon storage or fluxes. Although forest harvesting causes short-term changes in carbon sequestration during the period of stand regeneration, it generally has little impact on long-term wetland soil carbon balance (Roulet 2000; Trettin et al., 2011).

Wetland restoration usually includes the re-establishment of hydrological regimes to support hydrophytic vegetation. Wetland restoration and creation of new wetlands (where none existed previously) and small ponds have counteracted much of the wetland losses in CONUS (Dahl 2011). For instance, from 1998 to 2004 and 2004 to 2009, areas reclassified as wetlands in the United States increased by 17%, meaning that 802 km^2 of new wetlands were created, but this figure does not indicate how many additional square kilometers of the restored wetlands were still classified as wetlands. In addition, creation of small ponds has increased over the last few decades, with 838 km^2 per year created from 2004 to 2009 (Dahl 2011).

Wetland restoration can lead to the opposite effects of drainage, with increases in carbon pools and in CH_4 fluxes and lower CO_2 fluxes (Wickland et al., 2014). Research has found that restoring wetlands by rewetting them increases soil carbon storage (Lucchese et al., 2010). IPCC guidelines for mineral soil wetlands state that cultivation leads to losses of up to 71% of the soil organic carbon in the top 30 cm of soil over 20 years and that restoration increases depleted soil carbon pools by 80% over 20 years, and by 100% after 40 years (Wickland et al., 2014). Rewetting also may increase CH_4 fluxes, not only above the previously drained levels, but also above reference levels temporally (Badiou et al., 2011). However, some studies have found that restoration did not increase CH_4 fluxes (Richards and Craft 2015). In the long term, restoring degraded wetlands appears to be a positive for GHG mitigation.

Creating new wetlands and small ponds also can affect both long-term soil carbon storage and gaseous fluxes. Created wetlands tend to have carbon accumulation rates higher than those of natural wetlands (Bridgham et al., 2006). In addition, created wetlands often have similar or lower CH_4 fluxes (Mitsch and Hernandez 2013; Winton and Richardson 2015). However, assessments have found that small ponds are large sources of CH_4 (Holgerson and Raymond 2016). Similar to created wetlands and some riparian zones, small ponds may sequester carbon at high rates due to high sediment deposition rates from the surrounding land.

Many restored wetlands do not provide the level of ecosystem services they did before their degradation, usually a result of inadequate hydrology restoration. One survey found that only 21% of wetland restoration sites have ecologically equivalent natural functions (Turner et al., 2001). Post-restoration monitoring is critical to determining restoration success and providing opportunities to modify restoration techniques if necessary. Assessment of success usually occurs over relatively short periods (1 to 3 years) and with relatively simple protocols because of time, resource, and technical constraints. Determining success over the short term is difficult because wetland processes, such as soil formation or forest recovery, occur over decades. Also, most current assessment techniques are fairly simple and may not adequately characterize the condition of a wetland, especially if critical functions such as hydrology or processes such as carbon and nutrient cycling are not fully understood. Moreover, inadequate study of many wetland types challenges efforts to understand both the processes that lead to carbon accumulation and fluxes and the impact of wetland restoration on carbon. Furthermore, due to the developmental trajectory of restored wetlands, their capacity to store carbon may change through time, with considerable storage initially and then much less storage thereafter once vegetation has fully colonized and root systems have developed (Anderson et al., 2016).

13.4.2 Processes and Policies that Affect Wetland Management, Restoration, and Creation

Recognition of the values that wetlands provide has led to changes in federal policies aimed at protecting, restoring, and creating wetlands over the past

four decades. Four significant policies are 1) Section 404 of the Clean Water Act (1972); 2) the Highly Erodible Land Conservation and Wetland Conservation Compliance provisions of the 1985 Food Security Act and subsequent amendments, commonly known as the "Swampbuster program"; 3) President George H. W. Bush's "no net-loss" policy (1989); and 4) the U.S. Army Corps of Engineers and EPA compensatory mitigation rule (USACE 2008). Initially passed as part of the Federal Water Pollution Control Act of 1972, the Clean Water Act focused on nonagricultural wetland conversions (U.S. EPA 2015). In its initial form, the Swampbuster program discouraged farmers from converting wetlands by withholding federal farm program benefits if conversion occurred on nonexempt wetlands. Farm Bill 1990 amendments created the Wetland Reserve Program, which was later consolidated with other easement programs into the Agricultural Conservation Easement Program (ACEP). Rather than withholding incentives, the USDA NRCS incentivizes farmers to restore, protect, and enhance wetlands by purchasing wetland reserve easements via ACEP (USDA 2014). The Agricultural Act of 2014 (i.e., Public Law 113-79, commonly referred to as the 2014 Farm Bill) provided NRCS with the authority to enroll wetlands in 1) permanent easements, with 100% of the easement value and 75% to 100% of restoration costs covered, 2) 30-year easements funded at 50% to 75% of the easement value with 50% to 75% of the restoration costs covered, and 3) term easements with stipulations dependent on state laws.

The no net-loss policy, which sought to replace lost wetland habitat with new habitat by restoring and creating wetlands, is now the cornerstone of U.S. wetland conservation (Mitsch and Gosselink 2015). As a result, numerous federal and state agencies, non-governmental organizations, and private landowners are engaged in wetland restoration and creation across the United States with a keen focus on establishing the proper hydrological conditions needed to support flora and fauna specific to a certain wetland type. Such activities often result in preserving or expanding the carbon pool of wetlands, but little attention has been given to ensuring the long-term sustainability of such newly formed carbon sinks. Wetland restoration is still a relatively new field, and management approaches for maintaining the sustainability of carbon sinks are still being developed, tested, and refined.

The Federal Policy on Wetland Conservation in Canada (Canadian Wildlife Service 1991) also encourages no net-loss of wetlands. The regulation is focused largely on activities undertaken by the Canadian government on its federal land. Although the policy discourages wetland destruction or degradation, the Canadian government does not require compensatory mitigation. Though currently limited, the Natural Protected Areas Commission of Mexico has a national wetland policy to protect wetlands and avert losses.

13.5 Terrestrial Wetland Trends and Feedbacks

An important concern globally is how wetlands will respond to a changing climate. Climate change has the potential to affect carbon cycling of natural, degraded, created, and restored wetlands. However, there is considerable uncertainty regarding the likely responses, including how warming and variations in precipitation regimes will influence the balance between plant productivity and organic matter decomposition. An example pattern might be warming followed by drier conditions leading to wetland carbon losses, as has occurred in simulated peatland droughts (Fenner and Freeman 2011). Altered precipitation regimes also may shift the hydrological balance in the absence of warming. Even on an annual timescale, individual wetlands can alternate between a carbon sink in wet years to a carbon source in dry years, illustrating the sensitivity of wetlands to biotic and abiotic conditions. However, the direct correspondence of increased peat oxidation with a lowered water table is not universal. Instead, Makiranta et al. (2008) showed soil temperature controlled more of the variability in peatland soil respiration than did the water-table position. Similarly, CH_4 fluxes in high-latitude wetland ecosystems with high

water tables were more sensitive to soil temperature than were those ecosystems with lower water tables, which were more sensitive to water-table position (Olefeldt et al., 2013). Accordingly, changes in carbon pools and fluxes in response to changes in temperature and precipitation regimes will vary greatly based on wetland type and interactions with hydrology because carbon cycling may be different under warmer and wetter conditions than under warmer and drier conditions. For example, CH_4 fluxes from PPR wetlands were four times higher under warmer and wetter conditions than the fluxes were under warmer and drier conditions (Bansal et al., 2016). Northern seasonally frozen peatlands already are undergoing rapid changes, and increased carbon fluxes are likely to continue over the coming decades to centuries as conditions continue to warm (Schuur et al., 2015). Another general pattern is that drier conditions will facilitate and exacerbate fires, especially in peatlands, resulting in large fluxes from the oxidized peat (Turetsky et al., 2011b; see also Ch. 11: Arctic and Boreal Carbon, p. 428).

The response of mineral soil wetlands to changes in temperature and precipitation regimes is uncertain, largely because of the wide range in properties and geomorphic setting. Histic-mineral soil wetlands ("histic" refers to soils with a 20- to 40-cm organic horizon) may be expected to respond similarly to peatlands. For other types, such as mineral soil wetlands in floodplains where the surface organic layer is thin due to high turnover rate, the changes in that layer associated with climate change are likely small. Changes in the hydrological regime also are expected to alter the carbon balance. Increased periods of a high water table or flooding may be expected to reduce productivity (Trettin et al., 2006) and increase CH_4 fluxes (Sharitz and Pennings 2006). The effect of climate change on organic matter decomposition and carbon export from the wetland is an important uncertainty and feedback to adjoining aquatic ecosystems. The uncertainty in mineral soil wetland response is high, largely because there are far fewer studies on mineral soil wetlands than on peatlands.

Rising atmospheric CO_2 is considered likely to increase GHG fluxes from wetlands due to increased CH_4 fluxes offsetting gains from increased plant carbon sequestration (Bridgham et al., 2007; Hyvonen et al., 2007). Hyvonen et al. (2007) suggest that soil carbon in the temperate and boreal zones will increase because of increased litter input, but the magnitude of the response will depend on available nitrogen and land management. Little is known about interactions between changes in water regime and plant productivity. In upper Michigan, lowered water tables led to increased productivity in vascular plants (e.g., shrubs and sedges) and *Polytrichum*; higher water tables led to higher *Sphagnum* production (Potvin et al., 2015). Demonstrating the importance of field experimentation, Dijkstra et al. (2012) measured increases in CH_4 in both mineral soil wetlands and peatlands following manipulation of the water regime. Understanding these interactions with CH_4 fluxes is fundamental to considering the feedback associated with rising atmospheric CO_2 (Petrescu et al., 2015; Zhang et al., 2017b).

13.6 Global, North American, and Regional Context

13.6.1 Global and Continental Perspectives

Observational studies suggest that wetlands cover an estimated 8.2 million km^2 globally (Lehner and Döll 2004). However, based on recent studies that use both observations and models, the mean global area may be 12.3 million km^2 (Melton et al., 2013). The largest concentrations of wetlands generally are found between 50° and 70°N latitude, with substantial concentrations also found between 0° to 10°S latitude (Lehner and Döll 2004). North of 70°N latitude, continuous permafrost ecosystems also contain considerable soil carbon (see Ch. 11: Arctic and Boreal Carbon, p. 428). Wetlands are estimated to cover approximately 2.2 million km^2 in North America (see Table 13.1, p. 514), or about 9% of the continental land area. Although approximate global and regional extents of wetlands are generally known, there are significant challenges that hinder estimating wetland coverage with a high degree of

confidence. These challenges include, but are not limited to, lack of detailed inventories, nonuniform definitions of wetlands, limitations of remotely sensed data and models, and continuing drainage and conversion of wetlands worldwide.

Positioning the North American wetland carbon stock in a global context is difficult due to the broad range (300 to 530 Pg C) reported (Mitra et al., 2005). Accordingly, the North American wetlands (161 Pg C) compose a significant but uncertain proportion (30% to 54%) of the global wetland carbon stock.

Natural wetlands are the largest natural source of CH_4 fluxes to the atmosphere (Kirschke et al., 2013) and thus are an important consideration of large-scale modeling assessments. Saunois et al. (2016) conducted a comprehensive assessment of the global atmospheric CH_4 budget using "top-down" and "bottom-up" approaches, which respectively are based on inversions of atmospheric CH_4 data and process-based wetland biogeochemical models. Twenty top-down and 11 bottom-up estimates were provided for North American wetland fluxes averaged from 2003 to 2012. The multimodel mean (±1 standard deviation) was 16 ± 4 Tg CH_4-C emitted per year for the top-down estimates, and 35 ± 11 Tg CH_4-C per year for the bottom-up estimates. Boreal North America (i.e., Alaska and Canada) account for most of the difference between these two estimates, with the bottom-up approaches exceeding the top-down approaches by 19 Tg CH_4-C per year. Estimating the CH_4 flux from North American wetlands between 1979 and 2008, Tian et al. (2010) estimated an average of 17.8 Tg CH_4-C per year. Those simulation approaches are less than the estimate of North American wetland fluxes reported in this chapter, 44.8 Tg CH_4-C per year (see Table 13.1, p. 514). Both approaches have relatively large uncertainty levels associated with the CH_4 flux. Extrapolation of measurement data across the wetland area presumes a uniform response that belies the considerable differences among wetlands across the landscape. The large-scale model assessments suffer from the same issue of not having the capacity to consider variation among wetlands, but they have the ability to accommodate some aspects of spatial variability. The relative correspondence of the wetland CH_4 flux attests to the merits of both the large-scale process-based models and the need for additional empirical studies, particularly on mineral soil wetlands, to provide a broad base for model validation.

13.6.2 Regional Perspectives—United States, Canada, and Mexico

Within North America, Canada has the greatest wetland coverage, with estimates ranging from 1.27 to 1.60 million km^2, followed by Alaska with an estimated 0.18 to 0.71 million km^2 of wetlands (Lehner and Döll 2004; Zhu and McGuire 2016). Estimates of terrestrial wetlands for CONUS from the USFWS National Wetlands Inventory (0.39 million km^2) and Mexico (~0.05 million km^2) are smaller than the total wetland area suggested by Lehner and Döll (2004), 0.45 and 0.16 million km^2, respectively. The reported soil carbon stock for CONUS terrestrial wetlands (12.6 Pg C) approximates the estimate (10.6 Pg C) provided through the U.S. EPA's National Wetland Condition Assessment (NWCA; Nahlik and Fennessy 2016). The relatively small difference in soil carbon stock is attributable to less wetland area as reported in the NWCA (a difference of about 11,000 km^2) and a shallower reporting depth (120 cm). Wetlands in Canada are dominated by peatlands, which harbor large carbon stocks estimated at 115 Pg C for this assessment (see Table 13.1, p. 514) and 150 Pg C by Tarnocai et al. (2005). The greatest concentration of wetlands is in the provinces of Manitoba and Ontario, which contain about 41% of Canada's wetlands (Mitsch and Hernandez 2013).

The recent cartographic assessment of Mexico's wetlands provides important new information about the distribution of wetlands and context for assessing their loss (Landgrave and Moreno-Casasola 2012). Inland marshes are found in deltaic regions of the southeastern states of Veracruz, Tabasco, and Campeche, where the floodplains have deep organic soils (Smardon 2006). Marshes also are found in mountain ranges of central Mexico and in localized

Table 13.2. Estimates of Wetland Area, Total Carbon Storage, Carbon Dioxide and Methane Fluxes, and Net Carbon Flux by Major U.S. Region[a–b]

Region	Wetland Area (km^2)	Total Carbon Storage[c] (Pg C)	CO_2 Exchange[d] (Pg CO_2 per Year)	CH_4 Exchange[e] (Pg CO_2e per Year)	Net Carbon Flux[f] (Pg C per Year)
Eastern United States[g]	271,482	3.8, 4.2	–0.18, –0.048	0.186, 0.187	–0.049, –0.013
Great Plains[h]	30,380	0.22	NR[i]	0.082	–0.02
Western United States[j]	10,114	0.06, 0.07	–0.005, 0.0002	0.002	–0.0015, 0
Boreal Alaska – North[k]	112,007	2.4	NR	0.020	–0.002
Boreal Alaska – South[k]	18,627	0.9	NR	0.006	0.001

Notes

a) From U.S. Geological Survey's LandCarbon Program. Cells with two numbers represent the reported minimum and maximum. Carbon amounts are in petagrams (Pg).

b) See references for uncertainty analyses for the respective regions.

c) Total carbon storage for the eastern United States, Great Plains, and western United States is for 2005 and is the sum of biomass (live and dead) and the upper 20 cm of soil; for Alaska, total carbon storage is the average stock from 2000 to 2009 and is the sum of biomass (live above ground, live below ground, and dead), moss, litter, surface organic soil layers, and the upper 1 m of mineral soil.

d) Carbon dioxide (CO_2) flux for the eastern United States, Great Plains, and western United States is for 2001 to 2005; for Alaska, it is for 2000 to 2009.

e) Methane (CH_4) flux for the eastern United States, Great Plains, and western United States is for 2001 to 2005 and is presented in CO_2 equivalent (CO_2e) using a global warming potential (GWP) of 21; for Alaska, the flux is for 2000 to 2009 and is presented in CO_2e using a GWP of 25. Note that CO_2e is the amount of CO_2 that would produce the same effect on the radiative balance of Earth's climate system as another greenhouse gas, such as CH_4 or nitrous oxide, on a 100-year timescale. For comparison to units of carbon, each kg CO_2e is equivalent to 0.273 kg C (0.273 = 1/3.67). See Box P.2, Global Carbon Cycle, Global Warming Potential, and Carbon Dioxide Equivalent, p. 12, in the Preface for more details.

f) Net carbon fluxes for the eastern United States, Great Plains, and western United States are for 2001to 2005; for Alaska, they are for 2000 to 2009.

g) Zhu and Reed (2014).

h) Zhu and McGuire (2011).

i) Not reported.

j) Zhu and Reed (2012).

k) Zhu and McGuire (2016).

areas in the Sonoran and Chihuhuan deserts where springs feed shallow swamps (Mitsch and Hernandez 2013). However, little is known about their carbon stock or CO_2 and CH_4 fluxes.

The U.S. Geological Survey's LandCarbon Program developed ecoregion estimates of current and future projections of carbon storage, net CO_2 exchange and CH_4 fluxes, and net carbon balance of U.S. wetlands (Zhu and McGuire 2010), providing context for the current assessment. Wetland area, carbon stocks, and fluxes were estimated using process-based models and land-use and land-cover maps. These estimates, originally reported by level II ecoregion in a series of reports, are summarized by region in Table 13.2, this page. The LandCarbon assessment provides a basis for regional comparisons using a common methodology. However, the reported pools and fluxes are substantially different than those included in Table 13.1, p. 514, which uses the National Wetlands Inventory as the basis for wetland area, summarizes geospatial databases for the pools, and synthesizes observational studies as the basis for the pools and fluxes.

13.7 Synthesis, Knowledge Gaps, and Outlook

13.7.1 Summary of Terrestrial Wetlands Carbon Cycling

North American wetlands constitute a significant proportion (37%) of the global wetland area. The uncertainty in wetland area for North America is relatively low because wetlands in CONUS and Alaska, Mexico, and Canada have relatively recent inventories and assessments. However, more information about soil carbon and vegetation biomass within the wetlands is needed to assess carbon pools and fluxes and reduce uncertainties in the estimates. Wetland soil type varies significantly with latitude, with Alaska and Canada having the majority of the peatland area. Mineral soil wetlands are predominant (79%) in CONUS and contain 38% of its wetland carbon stock. An important consideration regarding the estimate of carbon pools in peatlands, which consist of 58% of the North American wetland area, is that total depth of peat is seldomly reported, while the average depth commonly exceeds the typical assessment depths of 1 to 2 m. Peatlands contain approximately 80% of the North American carbon, a proportion that is likely to increase substantially if the entire peat depth were considered. Nonforested vegetation communities compose 44% of the wetland area in North America, contain approximately 43% of the carbon pool, and accumulate 47% of the net carbon gain.

Historically, the wetland loss in North America has been significant, particularly in CONUS. However, to assess contemporary losses, periodic inventories at the national scale are needed. Currently, only the United States has regular updates to its wetlands inventory. Restoration and creation of new wetlands are major offsets to loss of natural U.S. wetlands. Whether these new wetlands have the same carbon dynamics as natural wetlands is a major uncertainty that will become more important as restored wetlands become a larger proportion of the total wetland area. A global meta-analysis comparing 621 restored and created wetlands to 556 reference wetlands indicated that functions related to biogeochemical cycling (mainly to carbon storage) were 23% lower in the restored and created wetlands (Moreno-Mateos et al., 2012). Successful functioning of those wetlands will be critical to mitigate the long-term losses of carbon from degraded wetlands.

13.7.2 Knowledge Gaps and Associated Uncertainties in the Wetland Carbon Cycle

The following are some major gaps in current knowledge about the North American wetland carbon cycle.

1. Future wetland response to climate change is uncertain. Because temperatures are predicted to increase at greater rates at higher latitudes, northern temperate wetlands, especially peatlands, are expected to be the most affected. More uncertainty exists in the predictions of precipitation, changes in which could either mitigate or exacerbate carbon sequestration rates in terrestrial wetlands. Although contemporary measurements and modeling offer perspective, additional manipulative experiments—such as the U.S. Department of Energy's Spruce and Peatland Responses Under Changing Environments (SPRUCE) experiment in northern Minnesota (Hanson et al., 2017) and USDA's former PEATcosm experiment in the Upper Peninsula of Michigan (Potvin et al., 2015)—are critical to test how wetlands will respond to changes in temperature and hydrological regime in the field. Work in mineral soil wetlands is particularly needed because of the paucity of studies and the functional linkages with aquatic systems.

2. Greater understanding is needed of the factors controlling carbon cycling in wetlands. Additional measurements of GHG fluxes and processes regulating the fluxes and carbon storage using improved inventories and methods at multiple spatial scales are required to 1) understand the interactions of soil, vegetation, and climatic factors; 2) provide a basis for quantifying fluxes to reduce significant uncertainties; and 3) evaluate biogeochemical and inverse-atmospheric models.

Particularly needed are studies that assess convergence across diverse spatial and temporal scales or lead to a process-based understanding of why convergence does not occur.

3. Dissolved carbon export, including both DIC and DOC, is a major uncertainty in the wetland carbon cycle. Dissolved carbon affects water quality and is an important food source for aquatic systems and estuaries, and dissolved gases may contribute to atmospheric loading. Understanding the mechanisms controlling dissolved carbon production and transformation is a major gap requiring field and watershed-scale assessments.

4. A better understanding is needed of the relationship between the sustainability of stored carbon and the particular chemistry of the carbon compounds that make up the carbon sink. Preliminary research shows that polyphenol content may serve to preserve peats under moderate drought conditions (Wang et al., 2015), but little is known about either the exact types of polyphenols or the plant communities that have the highest sustainability under projected climate and environmental conditions.

5. Data on restored and managed wetlands are sparse and insufficient to support assessment and modeling needs. Measurements to document the carbon balance in these wetlands are needed. Also necessary are standardized measurements and methods for collecting basic data in the field at the same depth and for analyzing parameters such as bulk density and percent of organic carbon. Monitoring of wetland restoration needs to extend through the entire trajectory of the project to gain a functional understanding of the differences in gaseous fluxes and carbon accumulation between natural and restored wetlands.

13.7.3 Tools for Assessing the Wetland Carbon Cycle

Due to the extremely wide variation in wetlands across North America, as well as the certainty that there will never be enough measurements to adequately quantify the wetland carbon stocks and fluxes, models present the means to represent the biophysical processes inherent to wetlands at variable spatial scales. Those tools provide needed capabilities to inform conservation, management, and mitigation strategies to sustain ecosystem services inherently linked to the wetland and global carbon cycle. Models also are useful for addressing the uncertainties within the carbon cycle and, in turn, for focusing field monitoring and experiments to fill critical information gaps. Mechanistic models provide the capabilities for simulating the processes that regulate carbon dynamics in wetlands reflecting the myriad soil, vegetation, and climatic conditions and management influences. Because of the water table's regulatory function in the wetland carbon cycle, an accurate representation of wetland hydrology is critical to model performance. There are fewer models for wetlands compared to those for uplands. Among biogeochemical models that are widely applicable to terrestrial wetlands and have the broadest capabilities with respect to soil and vegetation types are the Forest DNDC (or DeNitrification DeComposition) model, which was identified by USDA in the development of its carbon accounting framework (Ogle et al., 2014), and the DayCent model (Parton et al., 1998), which is widely used in grassland and agroecosystem simulations. Scaling wetland hydrology within a biogeochemical model is difficult; hence, coupling a biogeochemical model with a hydrological model can provide an effective basis for considering the inherent spatial variability among uplands and wetlands (Dai et al., 2012a). Simulating CH_4 fluxes is particularly difficult because of various interactions among controls of CH_4 production and transport from wetlands, including ebullition, that vary over very short distances such as 10 m or less (Bridgham et al., 2013). Correspondingly, uncertainties associated with plant carbon allocation and organic matter quality and decomposition impair the ability of field-scale biogeochemical models to predict CH_4 flux from the soil surface. These considerations are particularly important for small-scale models that are evaluated with field data.

Another major challenge to modeling carbon dynamics in wetlands is the inherent heterogeneity

of conditions within a wetland and the spatial heterogeneity of wetlands across the landscape. Accordingly, new approaches for accommodating high-resolution geospatial data with robust biogeochemical models are needed to provide capabilities to simulate wetland carbon dynamics at large scales. Such capabilities, in turn, would provide a basis for linking wetland biogeochemical models with atmospheric models (Gockede et al., 2010), thereby improving the basis for simulating the effects of climate change on wetland carbon. Large-scale bottom-up and top-down models are providing those capabilities to address CH_4 fluxes at the regional and global scales (Melton et al., 2013; Saunois et al., 2016; Bloom et al. 2017; Zhang et al., 2017a). However, estimates among the CH_4 models can vary considerably (Miller et al., 2016). Correspondingly, there is a real need for tools to assess wetland NEE; unfortunately, the large-scale models for assessing wetland NEE are not available or widely reported. Accordingly, ecosystem models must be upscaled to develop the components to simulate wetland NEE.

SUPPORTING EVIDENCE

KEY FINDING 1

The assessment of terrestrial wetland carbon stocks has improved greatly since the *First State of the Carbon Cycle Report* (CCSP 2007) because of recent national inventories and the development of a U.S. soils database. Terrestrial wetlands in North America encompass an estimated 2.2 million km^2, which constitutes about 37% of the global wetland area, with a soil and vegetation carbon pool of about 161 petagrams of carbon that represents approximately 36% of global wetland carbon stock. Forested wetlands compose 55% of the total terrestrial wetland area, with the vast majority occurring in Canada. Organic soil wetlands or peatlands contain 58% of the total terrestrial wetland area and 80% of the carbon (*high confidence, likely*).

Description of evidence base

Key Finding 1 is supported by an extensive analysis of the most current wetland soil and vegetation information available across the conterminous United States (CONUS), Alaska, Hawai'i, Puerto Rico, Canada, and Mexico, updating previous estimates made in SOCCR1 (see SOCCR2 Appendices 13A, p. 547 and 13B, p. 557).

Major uncertainties

Uncertainties are high where wetlands are present but not extensively mapped, such as in Alaska.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Over much of the area under consideration, confidence is high that this assessment has accurately mapped carbon pools in mineral soil wetlands and peatlands.

Estimated likelihood of impact or consequence, including short description of basis of estimate

Understanding current carbon pools is critical in predicting how changes in, for example, climate, land use, and restoration will affect the carbon stored in terrestrial wetlands.

Summary sentence or paragraph that integrates the above information

Terrestrial wetlands are the largest reservoir of carbon in North America. Understanding the processes that lead to carbon storage and fluxes is important to predict how future changes will influence this large carbon pool and subsequent feedbacks to the atmosphere.

KEY FINDING 2

North American terrestrial wetlands currently are a carbon dioxide sink of about 123 teragrams of carbon (Tg C) per year, with approximately 53% occurring in forested systems. However, North American terrestrial wetlands are a natural source of methane (CH_4), with mineral soil wetlands emitting 56% of the estimated total of 45 Tg as CH_4 (CH_4-C) per year (*medium confidence, likely*).

Description of evidence base

Key Finding 2 and this chapter's narrative are based on the most recently reported wetland inventories integrated with reported values of soil carbon density (mass per unit area) and gaseous

fluxes of carbon dioxide (CO_2) and CH_4. Accordingly, the projections are dependent on estimates of wetland area and the pool and flux values assigned to the wetland types (see Appendices 13A, p. 547, and 13B, p. 557).

Major uncertainties

Similar to Key Finding 1, one major uncertainty is the mapped area, especially in areas with considerable wetlands that have not been adequately mapped. A second important uncertainty are the flux rates, which are applied globally to wetland types but are highly variable in time and space. Moreover, in many cases, few data exist.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Confidence is medium, given both the incompleteness in mapping and variability in flux rates.

Estimated likelihood of impact or consequence, including short description of basis of estimate

Greenhouse gas fluxes from terrestrial wetlands in North America contribute to the global CO_2 and CH_4 cycles and associated climate forcing.

Summary sentence or paragraph that integrates the above information

Understanding both terrestrial wetland carbon pools (Key Finding 1) and net fluxes to the atmosphere (Key Finding 2) is critical because these wetlands are stable long-term carbon sinks and also an important source of CH_4.

KEY FINDING 3

The current rate of terrestrial wetland loss is much less than historical rates (about 0.06% of the wetland area from 2004 to 2009) with restoration and creation nearly offsetting losses of natural wetlands. Although area losses are nearly offset, there is considerable uncertainty about the functional equivalence of disturbed, created, and restored wetlands when comparing them to undisturbed natural wetlands. Correspondingly, there remains considerable uncertainty about the effects of disturbance regimes on carbon stocks and greenhouse gas (GHG) fluxes. For this reason, studies and monitoring systems are needed that compare carbon pools, rates of carbon accumulation, and GHG fluxes across disturbance gradients, including restored and created wetlands. Those studies will produce data that are needed for model applications (*high confidence, likely*).

Description of evidence base

The evidence for Key Finding 3 is from updated published literature for the United States and Mexico (Casasola 2008; Landgrave and Moreno-Casasola 2012; USFWS 2011) and the same data reported in SOCCR1 (CCSP 2007) for Canada. The amount of wetlands being restored is also a function of recent literature estimates (e.g., Dahl 2011). Disturbance also needs to be considered in the context of changes to carbon cycling processes.

Major uncertainties

Where wetlands are mapped well, the area of wetland loss is very certain. Some areas not mapped well, such as remote locations in Alaska, generally are not under threat from development, but changes in climatic conditions threatened the boreal region more than temperate and tropical

regions. However, the opposite is true for areas under development in Mexico. The amount of area being restored is also not tracked very well, especially when restoration fails. Crossing the gradient from disturbed to restored and/or created wetlands, there exists considerable uncertainty about the level of functions that those wetlands provide.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is high confidence that systems for reporting wetland losses and gains are accurate in the United States, but periodic inventories in other countries are lacking. Also, tracking the amount of wetlands that have been disturbed in some way is very difficult.

Estimated likelihood of impact or consequence, including short description of basis of estimate

Although the area of restored or created wetlands is small relative to the total wetland area of North America, the impact is likely important because understanding even small changes in wetland area is critical to scaling up carbon pools and fluxes.

Summary sentence or paragraph that integrates the above information

Although there are very reliable data that track wetland change across CONUS, no such data are available for Canada because regular wetland assessments for that country are lacking. In addition, field-based wetland mapping is generally poor in Alaska and Mexico, and restored and disturbed wetland areas also are difficult to track.

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Appendix 13A
Terrestrial Wetland Area and Carbon Pools

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13A.1 Introduction

This appendix provides the methodologies and data used to estimate the area and carbon pools of terrestrial wetlands in North America. Since the *First State of the Carbon Cycle Report* (SOCCR1; CCSP 2007), several developed geospatial databases have provided the opportunity to improve the estimation of carbon pools beyond what is feasible using area density factors. The development of the Gridded Soil Survey Geographic (gSSURGO) database by the U.S. Department of Agriculture's (USDA) Natural Resources Conservation Service (NRCS) was a particularly important advancement, availing gridded soil survey information for the United States and Puerto Rico. Similarly, the USDA Forest Service's Forest Inventory and Analysis (FIA) database uses forest biomass data for the United States, thereby facilitating its incorporation into carbon pool assessments. Sections 13A.2–13A.6 detail the data and methods used to obtain the reported wetland area and carbon pools.

13A.2 Conterminous United States

13A.2.1 Approach

The U.S. Fish and Wildlife Service's (USFWS) National Wetlands Inventory (NWI) was used as the basis for identifying terrestrial (i.e., nontidal) freshwater wetlands within the conterminous United States (CONUS) and for distinguishing between forested and nonforested wetlands. Subsequently, geospatial databases were used to calculate the carbon pools in soils and forests. Specifically, the gSSURGO database was used to calculate soil carbon, and the FIA database was used to calculate forest carbon based on the reported biomass. A carbon pool density factor was used for the nonforest vegetation biomass because an appropriate geospatial database was not available.

13A.2.2 Data

The datasets used for analyses of the wetland area and carbon pool computations are summarized in Table 13A.1, this page.

Table 13A.1. Source Datasets

Dataset	Year	Publisher	Download Link
Gridded Soil Survey Geographic (gSSURGO)	2016	U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS)	gdg.sc.egov.usda.gov
National Wetlands Inventory (NWI)	2015	U.S. Fish and Wildlife Service	www.fws.gov/wetlands/Data/State-Downloads.html
Forest Inventory Analysis (FIA) Forest Biomass	2003	USDA Forest Service FIA	data.fs.usda.gov/geodata/rastergateway/biomass/index.php
Value-Added Look Up Table Database	2016	USDA NRCS	gdg.sc.egov.usda.gov
Cartographic Boundary	2015	U.S. Census Bureau	www.census.gov/geo/maps-data/data/cbf/cbf_state.html

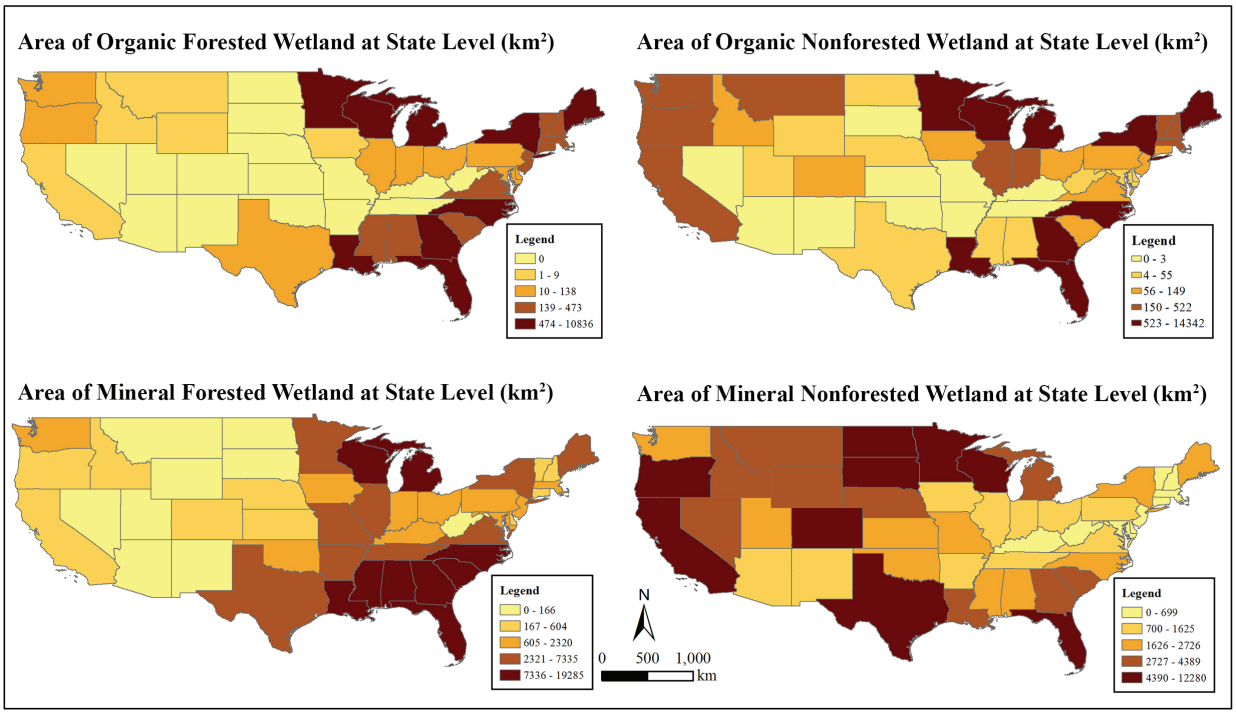

Figure 13A.1. Areal Distribution Among U.S. States of the Four Categories of Freshwater Terrestrial Wetlands. These wetland types are organic forested, organic nonforested, mineral forested, and mineral nonforested.

13A.2.3 Results

Wetland Area

According to NWI data, there are 395,197 km² of terrestrial freshwater wetlands in CONUS, 54% of which are forested and 46% nonforested (see Table 13A.2, this page). The estimate of forested freshwater wetlands is within 2% of the most recent NWI report; the total area of freshwater forested wetlands is calculated as 213,914 km², compared with 208,912 km² for 2009 from Dahl (2011). This area is smaller than the wetland area used in SOCCR1 (405,670 km²; CCSP 2007) because that report also included tidal wetlands. Mineral soils compose 79% of the terrestrial wetlands, with 21% being organic or peat soils (see Table 13A.2, this page). The distribution of wetlands among soil (organic and mineral) and vegetation (forest and nonforest) categories among states is presented in Figure 13A.1, this page.

The accuracy of the NWI data is considered to be over 90% for large wetlands (i.e., those > 1 hectare); uncertainties increase with smaller wetlands (Nichols 1994). Independent field-based studies also have been conducted to evaluate the accuracy of the NWI data for wetland mapping. The reported accuracies ranged from over 90% of overall accuracy in Michigan, Maine, and Massachusetts (see Kudray and Gale 2000; Nichols 1994; Swartwout et al., 1981) to underestimation of wetland area by 39% in Vermont

Table 13A.2. Area of Forested and Nonforested Terrestrial Wetland and Related Soil Types in the United States

Soil Type	Forested Wetlands (km²)	Nonforested Wetlands (km²)	Total (km²)
Organic Soil	40,823	42,903	83,726
Mineral Soil	173,091	138,381	311,472
Total	213,914	181,283	395,197

(see Morrissey and Sweeney 2006). With these issues considered, the NWI data are recognized as a reasonable source for estimating wetland area, particularly at large spatial extents, and thus are the source for national-level reporting.

Wetland Carbon Stock Estimation

Carbon stocks were calculated based on soil carbon content calculated from gSSURGO, forest biomass extracted from the FIA database, and a biomass density factor for nonforest vegetation. Forest vegetation consists of a carbon stock of about 0.878 petagrams of carbon (Pg C), with 79% occurring on mineral soils; nonforest vegetation contributed approximately 0.093 Pg C (see Table 13A.3, this page). Integrating forest biomass and soil carbon pools yields approximately 13.5 Pg C in terrestrial wetlands (see Table 13A.4, this page). The breakdown of carbon within forested and nonforested wetlands and of mineral and organic soils by state is summarized in Table 13A.4.

Table 13A.3. Carbon Stock in Forest and Nonforest Biomass Within Organic and Mineral Soil Terrestrial Wetlands[a]

Soil Type	Forest Carbon Pool (Pg C)	Nonforest Carbon Pool (Pg C)
Organic Soil	0.185	0.022
Mineral Soil	0.693	0.071
Total	0.878	0.093

Notes

a) Carbon stocks are measured in petagrams of carbon (Pg C) within the conterminous United States.

Table 13A.4. Carbon Stocks Within Organic and Mineral Soil, and Forested and Nonforested Freshwater Wetlands[a]

Soil Type	Forested Wetlands (Pg C)	Nonforested Wetlands (Pg C)	Total (Pg C)
Organic Soil	4.45	3.88	8.34
Mineral Soil	3.26	1.94	5.21
Total	7.71	5.82	13.55

Notes

a) Carbon stocks are measured in petagrams of carbon (Pg C) within the conterminous United States.

13A.3 Alaska

13A.3.1 Approach

The NWI and traditional soil surveys of Alaska are not available for the entire state. Fortunately, Clewley et al. (2015) recently published an inventory of wetlands based on remote-sensing data that used the Cowardin Classification system for representing the distribution of wetland types. Similarly, NRCS has produced a gSSURGO dataset for Alaska. Accordingly, those datasets were used as the basis for estimating the terrestrial wetland categories and carbon stocks following the same general approach used for CONUS. The combination of the wetland and carbon stock assessment with the distribution of frozen wetlands is considered to provide a comprehensive assessment of wetlands for the state.

13A.3.2 Data

Table 13A.5, p. 550, presents the principal datasets used in this study that include information on soil, wetlands, soil organic carbon, permafrost, and elevation.

13A.3.3 Results

Wetland Area

The total area of freshwater wetlands in Alaska, based on the Clewley et al. (2015) database, is 579,645 km^2 (see Table 13A.6, p. 550). The wetland data were classified from ALOS PALSAR[2] remote-sensing data using a random forest-based classifier. The data were processed using the adjustment factor employed by Clewley et al. (2015) to calculate the total area of freshwater wetlands, and data that overlapped into Canada were excluded. The overall accuracy of the classification is 84.5% for distinguishing specific wetland types and 94.7% for distinguishing wetlands with uplands (Clewley

[2] Advanced Land Observing Satellite-1 (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR)

Table 13A.5. Datasets Used to Estimate the Distribution and Carbon Stocks of Alaskan Terrestrial Wetlands[a–b]

Dataset	Year	Publisher	Download Link
Alaska Wetlands (Clewley et al., 2015)	2007	Alaska Satellite Facility	www.asf.alaska.edu/sar-data/palsar
STATSGO2	2014	U.S. Department of Agriculture (USDA) Natural Resources Conservation Service	www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_053629
Organic Soil Probability	2016	U.S. Geological Survey (USGS) LandCarbon	pubs.er.usgs.gov/publication/pp1826
Forest Biomass	2002	USDA Forest Service Forest Inventory and Analysis	data.fs.usda.gov/geodata/rastergateway/biomass
Probability of Near-Surface 1-m Permafrost	2015	USGS[a]	sciencebase.gov/catalog/item/5602ab5ae4b03bc34f5448b4
STATSGO Depth of Permafrost	2012	USGS[a]	ckan.snap.uaf.edu/dataset/depth-to-permafrost-alaska-landcarbon-project
STATSGO Permafrost Soil	2014	USDA Natural Resources Conservation Service[b]	www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_053629
Alaska State Boundary	2016	U.S. Census Bureau	www.census.gov/geo/maps-data/data/cbf/cbf_state.html
Elevation	1996	USGS	agdc.usgs.gov/data/usgs/erosafo/dem/dem.html

Notes

a) Provided by Neal Pastick, USGS.

b) Provided by Steve Campbell, USDA Natural Resources Conservation Service.

et al., 2015). The NWI class was used to aggregate the areas into forested and nonforested types.

Also calculated was the total area of wetlands in Alaska from STATSGO2 data using the percent in hydric soil attribute ("hydric_pct"; i.e., the percent in hydric soil). The total area is 587,143.9 km^2 based on the STATSGO2 percentage of hydric soils, which is very close to that provided by the Clewley et al. (2015) dataset.

Soil organic carbon data from STATSGO2 were employed to estimate the area of organic soils in Alaska, using the variable named "hydric_org_pct" (i.e., the percent in hydric organic soil) as the basis. This variable was multiplied by the area of map units (polygons) in the STATSGO2 dataset to obtain the area of peatland within each map unit. The total area of peatlands estimated from STATSGO2 using the hydric organic soil attribute is 107,057 km^2.

Table 13A.6. Area of Four Terrestrial Wetland Types in Alaska

Soil Type	Forested (km^2)	Nonforested (km^2)	Total (km^2)
Organic	9,947	97,111	107,057
Mineral	54,858	417,729	472,587
Total	64,805	514,840	579,645

Incorporating the distribution of organic soils into the overlay analyses yielded the distribution and area of the four wetland categories (see Figure 13A.2, p. 551). The total area of the four wetland

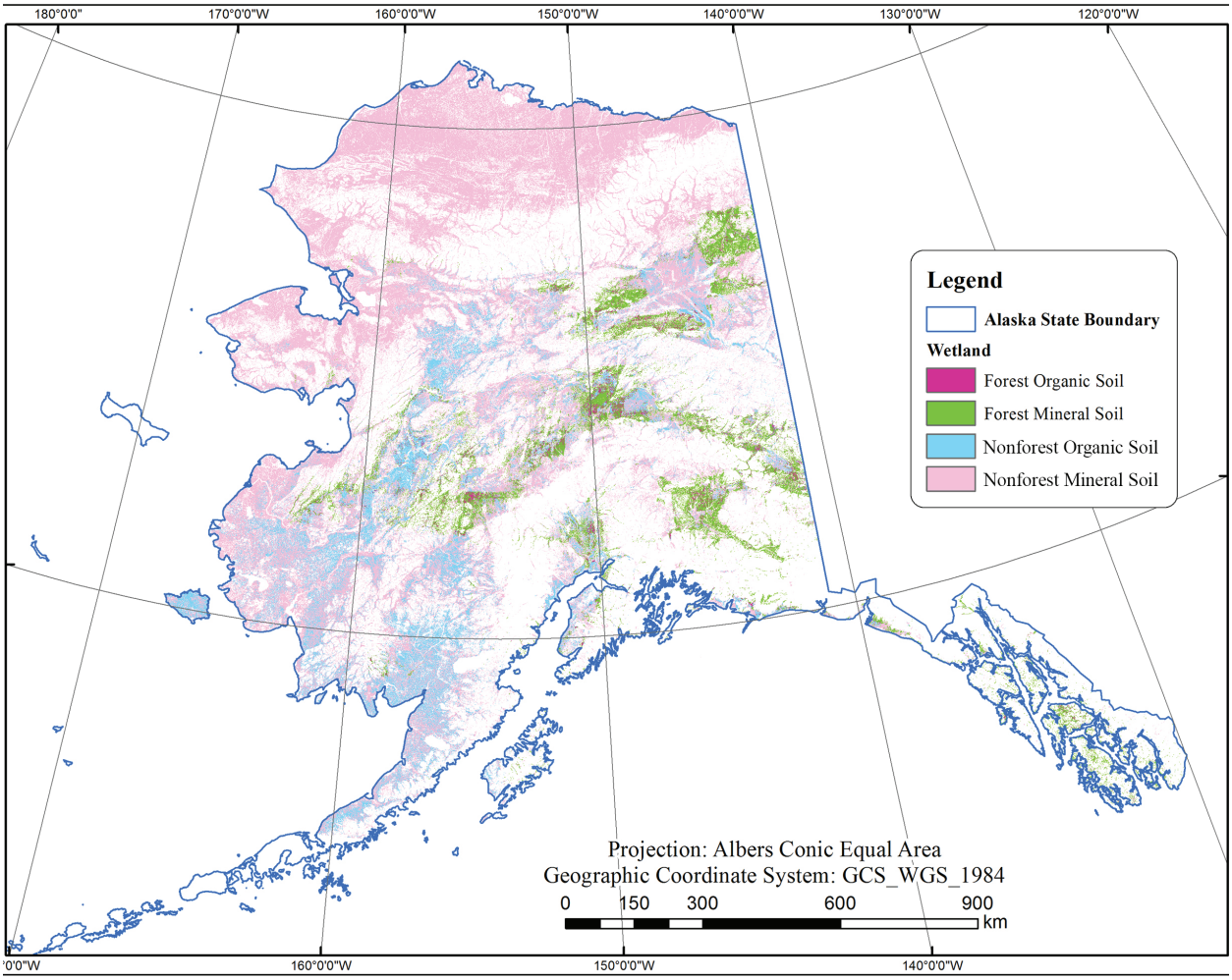

Figure 13A.2. Areal Distribution in Alaska of the Four Categories of Terrestrial Wetlands. These wetland types are forest organic soil, forest mineral soil, nonforest organic soil, and nonforest mineral soil.

categories of freshwater wetlands in Alaska are summarized in Table 13A.6, p. 550.

Assessing the overlap of wetlands and permafrost areas provided a basis for distinguishing carbon stocks. The use of the USGS probability map of permafrost provided a cut-off threshold of 60% to permafrost occurring within 1 m of the surface (with a 30-m spatial resolution). The resultant area of permafrost is 405,891 km^2, compared with 548,503 km^2 based on permafrost 2 m in depth from STATSGO2 data. Overlaying the USGS permafrost area with the wetlands shows that the total area of wetlands within the permafrost region is 267,887 km^2, which is approximately 46% of the total wetland area. The areas of the four types of freshwater wetlands in Alaska within permafrost or nonpermafrost regions are presented in Table 13A.7, p. 552.

Wetland Carbon Stocks

Ecosystem carbon stocks for the four wetland categories were derived from soil carbon stocks from USDA STATSGO data, biomass carbon data from FIA for forests, and a density factor for nonforested wetlands (see Table 13A.8, p. 552).

Table 13A.7. Distribution of Wetland Types Among Areas With and Without Permafrost in Alaska

Soil Type		Forested (km^2)	Nonforested (km^2)	Total (km^2)
Permafrost	Organic	4,199	23,274	27,474
	Mineral	14,696	225,716	240,413
	Total	18,895	248,991	267,887
Nonpermafrost	Organic	5,747	73,836	79,584
	Mineral	40,162	192,013	232,175
	Total	45,910	265,849	311,759

Table 13A.8. Total Carbon Pool of the Four Wetland Categories in Alaska[a]

Soil Type	Forested (Pg C)	Nonforested (Pg C)	Total Carbon (Pg C)
Organic	0.70	7.09	7.79
Mineral	2.80	21.21	24.01
Total	3.50	28.31	31.80

Notes

a) Carbon stocks are measured in petagrams of carbon (Pg C).

Partitioning the ecosystem carbon pools among wetlands in permafrost and nonpermafrost zones is provided in Table 13A.9, p. 553. Approximately 46% of the wetland carbon pool occurs within the permafrost areas.

13A.4 Puerto Rico

13A.4.1 Approach

The approaches to quantifying the distribution of terrestrial wetlands and the associated carbon pools for Puerto Rico follow those of CONUS, where a suite of datasets was used, including gSSURGO, NWI, Value-Added Look Up Table Dataset, Cartographic Boundary Shapefile, and FIA Forest Biomass Dataset. An overlay analysis was conducted between NWI and gSSURGO to identify vegetation and soil types for wetlands. Cartographic Boundary identified the boundary of Puerto Rico. The FIA Forest Biomass dataset provided the forest biomass information. Soil Data Development Tools for ArcGIS were used to extract the soil class of freshwater wetlands.

13A.4.2 Data

Datasets used in this study are summarized in Table 13A.10, p. 553.

13A.4.3 Results

Wetland Area

The total area of terrestrial wetlands derived from NWI data is 311.4 km^2. However, gSSURGO data coverage was missing for approximately 9.8% of the terrestrial wetland area. Distributing the area of missing soil data among the forested and nonforested categories yields the final area of the four wetland categories (see Table 13A.11, p. 553).

Ecosystem Carbon Pool

Ecosystem carbon pools, including soil and biomass, for freshwater wetlands in Puerto Rico are summarized in Table 13A.12, p. 553.

13A.5 Canada

13A.5.1 Approach

Canadian terrestrial freshwater wetlands were estimated based on a combination of spatial data because there was not a single wetland database that could produce estimates of organic and mineral soil wetlands and of forest and nonforest vegetation.

13A.5.2 Data

Datasets in this study are summarized in Table 13A.13, p. 554.

Table 13A.9. Ecosystem Carbon Pools in Freshwater Wetlands Occurring in Permafrost and Nonpermafrost Areas in Alaska[a]

Soil Type		Forested (Pg C)	Nonforested (Pg C)	Total Carbon (Pg C)
Permafrost	Organic	0.27	1.56	1.83
	Mineral	0.83	11.87	12.70
	Total	1.11	13.43	14.53
Nonpermafrost	Organic	0.42	5.54	5.96
	Mineral	1.97	9.34	11.30
	Total	2.39	14.88	17.26

Notes

a) Carbon stocks are measured in petagrams of carbon (Pg C).

Table 13A.10. Datasets Used to Estimate Terrestrial Wetland Area and Carbon Pools in Puerto Rico

Dataset	Year	Provider	Download Link
Gridded Soil Survey Geographic (gSSURGO)	2016	U.S. Department of Agriculture (USDA) Natural Resources Conservation Service	gdg.sc.egov.usda.gov
National Wetlands Inventory	2010	U.S. Fish and Wildlife Service	www.fws.gov/wetlands/Data/State-Downloads.html
Forest Biomass	2008	USDA Forest Service's Forest Inventory and Analysis	data.fs.usda.gov/geodata/rastergateway/biomass
Puerto Rico Boundary	2016	U.S. Census Bureau	www.census.gov/geo/maps-data/data/cbf/cbf_state.html

Table 13A.11. Area of Terrestrial Wetland Categories in Puerto Rico

Soil Type	Forested (km^2)	Nonforested (km^2)	Total (km^2)
Organic Soil	0.67	8.4	9.1
Mineral Soil	49.9	252.3	302.3
Total	50.6	260.7	311.4

Table 13A.12. Ecosystem Carbon Pools Among the Four Terrestrial Wetland Categories in Puerto Rico[a]

Soil Type	Forested (Pg C)	Nonforested (Pg C)	Total (Pg C)
Organic Soil	0.000	0.001	0.001
Mineral Soil	0.001	0.006	0.007
Total	0.001	0.007	0.008

Notes

a) Carbon pools are measured in petagrams of carbon (Pg C).

13A.5.3 Results

Organic and Mineral Soil in Forested and Nonforested Terrestrial Wetlands in Canada

Organic and mineral soils for forested and nonforested wetlands were estimated by overlaying land-cover datasets (GLWD and North America land-cover data) with soil datasets (FAO soil data, Peatland Database of Canada, and Soil Landscape of Canada). Those analyses routinely underestimated wetland area compared with estimates in published reports, especially for organic soils (Tarnocai 2006; Warner 2005; see Table 13A.14, p. 554, for examples of the differences in wetland area based on data sources).

Table 13A.13. Datasets Used in Canadian Terrestrial Wetland Assessment

Code[a]	Dataset	Year	Publisher	Download Link
W_1	North America Land Cover	2010	U.S. Geological Survey	landcover.usgs.gov/nalcms.php
W_2	Global Lakes and Wetlands Database Level 3 (GLWD-3)	2004	World Wild Life Organization; The Center for Environmental Systems Research, University of Kassel, Germany	worldwildlife.org/pages/global-lakes-and-wetlands-database
S_1	FAO/UNESCO[b] Digital Soil Map of the World 3.6	2007	Food and Agriculture Organization of the United Nations	fao.org/geonetwork/srv/en/metadata.show?id=14116
S_2	Soil Landscapes of Canada 3.2	2010	Agriculture and Agri-Food Canada	sis.agr.gc.ca/cansis/nsdb/slc/v3.2/index.html
S_3	Peatlands of Canada	2005	Natural Resources Canada	geogratis.gc.ca/api/en/nrcan-rncan/ess-sst/4e9e791c-ebad-594a-a3ba-14b8b974f239.html

Notes

a) The W_1 and W_2 and S_1, S_2, and S_3 abbreviations are used in this and subsequent tables to indicate, respectively, the wetlands and soils datasets outlined here.

b) Key: FAO, U.N. Food and Agriculture Organization; UNESCO, United Nations Educational, Scientific and Cultural Organization.

Table 13A.14. Areas of Forested Wetland and Nonforested Terrestrial Wetland and Related Soils in Canada[a–b]

Soil Type	$W_1 * S_1$ (km²)			$W_1 * S_2$ (km²)		
	Forested	Nonforested	Total	Forested	Nonforested	Total
Organic Soil	582,078	194,895	776,973	499,271	35,692	534,963
Mineral Soil	215,794	40,933	256,727	360,249	21,345	381,594
Total	797,872	235,828	1,033,700	859,520	57,037	916,557
Soil Type	$W_2 * S_1$ (km²)			$W_2 * S_2$ (km²)		
	Forested	Nonforested	Total	Forested	Nonforested	Total
Organic Soil	503,810	187,765	691,575	351,529	32,084	383,613
Mineral Soil	161,886	38,960	200,846	193,374	17,685	211,059
Total	665,696	226,725	892,421	544,903	49,769	594,672

Notes

a) Areas estimated using different data sources.

b) W_1: 2010 North America Land Cover dataset (wetland class available); W_2: Global Lakes and Wetlands Database; S_1: FAO/UNESCO Digital Soil Map of the World; S_2: Soil Landscapes of Canada; S_3: Peatlands of Canada dataset.

Asterisk (*) denotes the use of multiple datasets (GIS-based overlay analysis applied).

Table 13A.15. Areas of Forested and Nonforested Wetland and Related Soil in Canada from Peatland Dataset (S_3)[a]

Soil Type	Forested (km^2)	Nonforested (km^2)	Total (km^2)
Organic Soil	703,785	415,450	1,119,235
Mineral Soil	268,337	103,932	372,270
Total	972,122	519,382	1,491,505

Notes

a) S_3, Peatlands of Canada dataset.

Table 13A.16. Carbon Pools of Forested and Nonforested Wetland and Peat and Mineral Soils in Canada[a]

Soil Type	Forested (Pg)	Nonforested (Pg)	Total[a]
Organic Soil	76.7	37.8	114.5
Mineral Soil	5.1	9.5	14.6
Total	81.8	47.3	129.0

Notes

a) Carbon pools are calculated in petagrams (Pg).

Table 13A.17. List of Datasets Used to Assess the Area of Terrestrial Wetlands in Mexico

Dataset	Year	Publisher	Download Link
North America Land Cover	2010	U.S. Geological Survey, Natural Resources Canada, Insituto Nacional de Estadística y Geografía (INEGI), Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO), and Comisión Nacional Forestal (CONAFOR)	landcover.usgs.gov/nalcms.php
Mapa Potencial de Humedales	2012	INEGI	www.inegi.org.mx/geo/contenidos/recnat/humedales/datosvec.aspx

Because the accepted area of peatlands is 1,135,610 km^2 as reported by Tarnocai (2006), it was used as the basis for the total peatland area; the 16,375 km^2 of permafrost peatlands (Tarnocai et al., 2011) were excluded from the final area table (see Table 13A.15, this page). Wetland-specific soil types from the Peatlands of Canada and the Soil Landscapes of Canada datasets were used to identify mineral and organic soil wetlands. The analysis of wetland area in Canada is based on the Peatlands of Canada database, which was updated from its previous version. The accuracy of the wetland area estimated using this database is equal to or greater than 66%, as suggested by Tarnocai (2009). The distribution of terrestrial freshwater wetlands in Canada is presented in Table 13A.15. For comparison, Warner (2005) reported 1.056 million km^2 of peatland area (organic soil wetland) for Canada, a difference of 7%.

Carbon Pools

Carbon pools of the Canadian wetlands were calculated using the area carbon density factors for the four wetland categories, derived from CONUS (see Table 13A.16, this page).

13A.6 Mexico

13A.6.1 Approach

An assessment of terrestrial wetlands in Mexico was used as the basis for identifying wetland areas and soil types. The North American Land Cover dataset (see Table 13A.17, this page) and a recent dataset from Mexico were used to segregate the wetlands into vegetation categories. Area carbon density factors were used to develop the estimates of wetland carbon pools.

13A.6.2 Data

The datasets used to estimate the area of terrestrial wetlands in Mexico are presented in Table 13A.17.

Table 13A.18. Area of Freshwater Wetlands in Mexico Categorized by Soils and Vegetation

Soil Type	Forested (km^2)	Nonforested (km^2)	Total (km^2)
Organic Soil	3,394	17,191	20,585
Mineral Soil	5,288	10,320	15,608
Total	8,682	27,511	36,193

13A.6.3 Results

Organic and Mineral Soil in Forested and Nonforested Wetlands in Mexico

This estimate of freshwater wetlands is greater than other reported values (e.g., 31,000 km^2; Bridgham et al., 2006). A review of the map units from the Mapa Potencial de Humedales could not ensure that selected wetlands were adequately constrained to freshwater systems (due to problems with data code translations). Accordingly, the calculated wetland area was reduced by 25% to provide a conservative estimate (see Table 13A.18, this page), thereby reducing the accuracy to at least 75%. The metadata for the database did not provide an estimate of the mapping error.

Acknowledgments

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Appendix 13B
Terrestrial Wetland–Atmosphere Exchange of Carbon Dioxide and Methane

Prepared by Carl Trettin,[1] Judy Drexler,[2] Randall Kolka,[1] Scott Bridgham,[3] Sheel Bansal,[2] Brian Tangen,[2] Brian Bescoter,[4] Wenwu Tang,[5] and Steven Campbell[6]
[1]USDA Forest Service; [2]U.S. Geological Survey; [3]University of Oregon; [4]Florida Atlantic University; [5]University of North Carolina, Charlotte; [6]USDA Natural Resources Conservation Service

13B.1 Introduction

This chapter used published observational studies and recent syntheses to develop the basis for estimating both the net uptake of atmospheric carbon dioxide (CO_2) by terrestrial wetlands, which is equal to negative net ecosystem exchange (NEE), and the net fluxes of methane (CH_4) from terrestrial wetlands to the atmosphere. The primary source documents were the *First State of the Carbon Cycle Report* (SOCCR1; CCSP 2007) and the recent Intergovernmental Panel on Climate Change (IPCC) Wetlands Supplement (IPCC 2013). That information was augmented where possible with additional references. There were very few recent reports of measured NEE in comparison to reports on CH_4 flux. Accordingly, there was reliance on the previously published synthesis, with considerable uncertainty remaining in the NEE estimates. Tropical wetland fluxes were derived from the recent synthesis by Sjögersten et al. (2014).

Section 13B.2, this page, summarizes the observational data used as the basis for the area density flux factors. The flux estimates were based on those data and specific references, depending on the assessment area. Section 13B.3, p. 558, presents the area density flux factors used for each country and region.

Table 13B.1 Average Methane and Net Ecosystem Exchange for Nonforested and Forested Wetlands on Peat Soils[a–c]

Wetland Area	Average	Standard Error	n
CH_4 (g CH_4-C per m² per Year)			
Nonforested	23.6	3.1	73
Forested	8.9	5.2	14
NEE (g C per m² per Year)			
Nonforested	–135.0	42.5	14
Forested	–124.7	43.1	5

Notes

a) Negative net ecosystem exchange (NEE) indicates net transfer to the ecosystem.

b) See Tables 13B.8 and 13B.9 in Supplement, p. 561, for values and references.

c) Key: CH_4, methane; C, carbon; g, gram; n, number of studies.

13B.2 Literature Review

13B.2.1 Peat Soils

The mean CH_4 and NEE are presented in Table 13B.1, this page. The mean CH_4 flux rate for nonforested and forested wetlands are 23.6 and 8.9 grams (g) of CH_4-C per m² per year, respectively. In comparison, the mean CH_4 flux rate used for peatlands in SOCCR1 was 1.9 g CH_4-C per m² per year. The difference in CH_4 flux rates is attributable to the additional references and the wide range in conditions from the reported studies. The mean NEE for the nonforested and forested wetlands are –135.0 and –124.7 g C per m² per year, respectively. However, there are relatively few reports of measured NEE from peatlands; hence, the basis provided by the published studies is relatively weak. For SOCCR1, NEE was estimated on the basis of net changes in soil

and plant carbon, yielding an NEE of –19.0 to –121.0 g C per m^2 per year for northern and temperate peatlands (CCSP 2007). Plant carbon accumulation was considered negligible for the northern biomes, due the paucity of data. Accordingly, soil carbon accumulation accounted for 100% of the gain in the northern peatlands and 58% in the temperate peatlands.

13B.2.2 Mineral Soils

The mean CH_4 and NEE fluxes for mineral soil wetlands are presented in Table 13B.2, this page. The mean CH_4 flux rate for nonforested and forested wetlands are 26.1 and 26.9 g CH_4-C per m^2 per year, respectively. In comparison, the mean CH_4 flux rate used for mineral wetlands in SOCCR1 (CCSP 2007) was 6 g CH_4-C per m^2 per year. As was the case with the peatlands, the variation in CH_4 flux rates is due to the wide range in conditions from the reported studies. The mean NEE for the nonforested areas is –102.1 g C per m^2 per year. There were too few reports of measured NEE for mineral soil forests; hence, another metric was used. In SOCCR1, NEE was estimated on the basis of net changes in soil and plant carbon, yielding an NEE of –17 to –67 g C per m^2 per year, for northern and temperate mineral soil wetlands, respectively (CCSP 2007). For that analysis, plant carbon accumulation was considered negligible for the northern biomes, due in large part to the paucity of data. Accordingly, soil carbon accumulation accounted for 100% of the gain in the northern mineral soil wetlands and 25% in the temperate mineral soil wetlands.

Table 13B.2. Methane and Net Ecosystem Exchange Means and the Associated Standard Errors for Nonforested and Forested Wetlands on Mineral Soils[a–c]

Wetland Area	Mean	Standard Error	n
CH_4 (g CH_4-C per m^2 per Year)			
Nonforested	26.1	3.6	46
Forested	26.9	7.9	16
NEE (g C per m^2 per Year)			
Nonforested	–102.1	34.4	13
Forested	NA[d]	NA	

Notes

a) Negative net ecosystem exchange (NEE) indicates net transfer to the ecosystem.

b) See Tables 13B.10 and 13B.11 in Supplement, p. 561, for values and references.

c) Key: CH_4, methane; C, carbon; g, gram; n, number of studies.

d) Not applicable.

13B.3 Country and Regional Density Factors

13B.3.1 Conterminous United States

Carbon flux within the conterminous United States (CONUS) was estimated using area carbon flux density factors (see Table 13B.3, this page). The NEE flux density factors are based on the mean for the peat soil nonforested wetland and mineral

Table 13B.3. Flux Density Factors Used to Estimate Net Ecosystem Exchange and Methane Fluxes from Freshwater Wetlands in the Conterminous United States[a–d]

Flux	Organic Soil		Mineral Soil	
	Forested	Nonforested	Forested	Nonforested
NEE (g CO_2-C per m^2 per Year)	–120.97 (45.60)	–134.97 (42.53)	–66.99 (23.55)	–102.15 (34.43)
CH_4 (g CH_4-C per m^2 per Year)	8.90 (5.24)	23.58 (3.13)	26.93 (7.95)	26.09 (3.60)

Notes

a) Negative net ecosystem exchange (NEE) indicates net transfer to the ecosystem.

b) Standard error in parentheses.

c) Source: Appendix 13B Supplement: Carbon Pools and Fluxes, p. 561.

d) Key: CO_2, carbon dioxide; CH_4, methane; g, gram; C, carbon.

Table 13B.4. Area Density Factors Used to Estimate Net Ecosystem Exchange and Methane Flux from Freshwater Wetlands in Alaska[a–d]

Flux	Organic		Mineral	
	Forested	Nonforested	Forested	Nonforested
NEE (g CO_2-C per m² per Year)	–56.53 (32.14)	–56.53 (32.14)	–56.53 (32.14)	–56.53 (32.14)
CH_4 (g CH_4-C per m² per Year)	8.90 (5.24)	23.58 (3.13)	26.93 (7.95)	26.08 (3.60)

Notes

a) Negative net ecosystem exchange (NEE) indicates net transfer to the ecosystem.

b) Standard error in parentheses.

c) Source: Appendix 13B Supplement: Carbon Pools and Fluxes, p. 561.

d) Key: CO_2, carbon dioxide; CH_4, methane; g, gram; C, carbon.

soil nonforested wetlands (see Tables 13B.1 and 13B.2, p. 557 and p. 558, respectively). To estimate NEE for the forested wetlands, the SOCCR1 values (Bridgham et al., 2007) were used due to the small number of field-based reports. The estimate in SOCCR1 was based on the annual change in soil and plant carbon; the conservative estimate of 50 g C per m² per year sequestered in forests was used for both peat and mineral soil wetlands (Bridgham et al., 2007). The small number of studies that directly measure NEE in wetlands remains a constraint; hence, the segmented approach used by Bridgham et al. (2007) provides a functional basis.

The CH_4 flux density factors are based on the mean of data reported for the four wetland categories (see Section 13B.2, p. 557). These mean flux factors are similar to those used in SOCCR1 (CCSP 2007), where the mean for freshwater wetlands was 5.3 g CH_4-C per m² per year.

13B.3.2 Alaska

The available data for establishing the carbon flux for Alaska is very limited. The area density factor for NEE employs the values reported by He et al. (2016), which are based on simulation results (see Table 13B.4, this page). For the CH_4 flux, the mean values used were derived from the literature compilation (see Section 13B.2, p. 557). In comparison, He et al. (2016) estimated the CH_4 flux at 47.5 g C per m² per year, an amount which is almost twice the value used here; the paucity of data determined use of the more conservative CH_4 flux estimate based on field measurement data.

Table 13B.5. Area Density Factors Used to Estimate Net Ecosystem Exchange and Methane Flux for Tropical Terrestrial Wetlands[a–d]

Wetland Type	NEE	CH_4 Flux
	g C per m² per Year	
Organic Soil Wetland	–310.3 (152.8)	40.1 (17.1)
Mineral Soil Wetland	–120.8 (218.2)	54.0 (9.7)

Notes

a) Negative net ecosystem exchange (NEE) indicates net transfer to the ecosystem.

b) Standard error in parentheses.

c) Source: Sjögersten et al. (2014).

d) Key: C, carbon; g, gram; CH_4, methane.

13B.3.3 Puerto Rico

Estimates of NEE and CH_4 fluxes (see Table 13B.5, this page) were obtained using area density factors for mineral and organic soils derived from the synthesis of tropical wetlands provided by Sjögersten et al. (2014). The same area density factors were used for forested and nonforested wetlands.

Table 13B.6. Area Density Factors Used to Estimate Net Ecosystem Exchange and Methane Flux from Freshwater Wetlands in Canada[a–c]

Flux	Organic		Mineral	
	Forested	Nonforested	Forested	Nonforested
NEE (g CO_2-C per m² per Year)	–47.71 (4.18)	–16.71 (4.18)	–47.98 (12.74)	–102.15 (34.44)
CH_4 (g CH_4-C per m² per Year)	8.90 (5.24)	23.58 (3.13)	26.93 (7.95)	26.09 (3.60)

Notes

a) Negative net ecosystem exchange (NEE) indicates net transfer to the ecosystem.

b) Standard error in parentheses.

c) Key: CH_4, methane; CO_2, carbon dioxide; g, gram; C, carbon.

13B.3.4 Canada

Carbon flux for Canada was estimated using area carbon flux density factors (see Table 13B.6, this page) calculated on the basis of reported values. The area density factor for NEE in nonforested peatlands and mineral soil wetlands uses the mean reported from measurement studies (see Section 13B.2, p. 557). For forested wetlands, the value reported in SOCCR1 was used, reflecting the soil carbon accretion, to which was added 31 g C per m² per year sequestered in vegetation, an amount which is based on an 18-year assessment of Canadian forests (Stinson et al., 2011). The analyses of Stinson et al. (2011) did not include changes in soils as a result of bryophytes or sedimentation; hence, adding the soil component seemed appropriate because it was the only component used in SOCCR1 (CCSP 2007).

The CH_4 flux density factors are based on the data average reported for the four categories (see Section 13B.2, p. 557). These mean flux factors for peatlands are higher than the factor used in SOCCR1 (2.8 g C per m² per year). For freshwater wetlands, the SOCCR1 CH_4 flux was 5.3 g CH_4-C per m² per year, which is considerably lower than the forested and nonforested values (CCSP 2007).

Table 13B.7. Area Density Factors Used to Estimate Net Ecosystem Exchange and Methane Flux for Mexico[a–d]

Wetland Type	NEE	CH_4 Flux
	g C per m² per Year	
Organic Soil Wetland	–310.3 (152.8)	40.1 (17.1)
Mineral Soil Wetland	–120.8 (218.2)	54.0 (9.7)

Notes

a) Negative net ecosystem exchange (NEE) indicates net transfer to the ecosystem.

b) Standard error in parentheses.

c) Source: Sjögersten et al. (2014).

d) Key: CH_4, methane; g, gram; C, carbon.

13B.3.5 Mexico

Estimates of NEE and CH_4 fluxes (see Table 13B.7, this page) were obtained using area density factors for mineral and organic soils derived from the synthesis of tropical wetlands developed by Sjögersten et al. (2014). The negative number for NEE indicates net uptake by the ecosystem. The same area density factors were used for forested and nonforested wetlands.

Appendix 13B Supplement: Carbon Pools and Fluxes

Tables 13B.8–13B.11

Table 13B.8. Forested Peatland Area Density Flux Factors[a–b]

Location	Vegetation Type	NEE Emission (g CO_2-C per m^2 per Year)	CH4 Emission (g CH_4-C per m^2 per Year	Reference
New York	Forested peatland		0.150	Coles and Yavitt (2004)
Minnesota	Forest bog hummock		2.625	Dise (1993)
Minnesota	Forest bog hollow		10.350	Dise (1993)
Minnesota	Forest bog hollow		3.513	Dise (1992)
Minnesota	Hummock		1.317	Dise (1992)
Wisconsin	Forest bog	–80.0	0.800	Desai et al. (2015)
West Siberia	Pine peatland		0.132	Golovatskaya and Dyukarev (2008)
West Siberia	Stunted pine peatland		0.198	Golovatskaya and Dyukarev (2008)
Southern Germany	Bog	–62.0	5.300	Hommeltenber et al. (2014)
Boreal	Swamp	–256.0		Lu et al. (2017); Lund et al. (2010)
Boreal	Swamp	–195.5		Lu et al. (2017); Sulman et al. (2012); Syed et al. (2006)
Temperate	Bog	–30.0		Lu et al. (2017); Sulman et al. (2012); Syed et al. (2006)
West Virginia	Appalachian bog		74.646	Wieder et al. (1990)
Florida	Swamp		2.026	Villa and Mitsch (2014)
Florida	Swamp		1.661	Villa and Mitsch (2014)
Maryland	Appalachian bog		19.320	Wieder et al. (1990)
West Virginia	*Sphagnum*/Forest		2.625	Yavitt et al. (1990)

Notes

a) Negative net ecosystem exchange (NEE) indicates net transfer to the ecosystem.

b) Key: CO_2, carbon dioxide; CH_4, methane; g, gram; C, carbon.

Table 13B.9. Nonforested Peatland Area Density Flux Factors[a]

Location	Vegetation Type	Annual Flux (CO_2 g C per m^2 per Year)	Annual Flux (CH_4 g C per m^2 per Year)	Reference
Minnesota	Open bog		61.473	After Crill et al. (1988); after Mitsch and Wu (1995)
Minnesota	Natural fen		65.864	After Crill et al. (1988); after Mitsch and Wu (1995)
Minnesota	Acid fen		21.077	After Crill et al. (1988); after Mitsch and Wu (1995)
West Virginia	Mountain bog		51.374	After Gorham (1991); after Crill et al. (1988)
Minnesota	Bog		36.006	After Harriss et al. (1985)
Minnesota	Fen		1.098	After Harriss et al. (1985)
California	Marsh	–412.5	56.300	Anderson et al. (2016)
Minnesota	Open bog		0	Bridgham et al. (1995)
New Hampshire	Poor fen		82.950	Carroll and Crill (1997)
Boreal Canada	Swamp		0.922	Derived from Moore and Roulet (1995)
Boreal Canada	Fen		2.503	Derived from Moore and Roulet (1995)
Boreal Canada	Bog		1.713	Derived from Moore and Roulet (1995)
Minnesota	Fen Lagg		9.450	Dise (1993)
Minnesota	Bog (open bog)		32.325	Dise (1993)
Minnesota	Fen (open poor fen)		49.275	Dise (1993)
Minnesota	Open poor fen		13.173	Dise (1992)
Minnesota	Open bog		3.074	Dise (1992)
Minnesota	Poor fen, control		66.075	Dise and Verry (2001)
Minnesota	Poor fen, ammonium nitrate added		70.255	Dise and Verry (2001)
Minnesota	Poor fen, ammonium sulfate added		44.788	Dise and Verry (2001)
Minnesota	Nonforested		17.250	Dise and Verry (2001)
Wales	Peat monoliths		63.230	Freeman et al. (1993)
New Hampshire	Poor fen		51.975	Frolking and Crill (1994)
West Siberia	Sedge fen		14.490	Golovatskaya and Dyukarev (2008)
Florida	Wet prairie (marl)		5.625	Happell et al. (1994)
Florida	Marsh (marl)		6.131	Happell et al. (1994)
Florida	Marsh (marl)		10.125	Happell et al. (1994)
Florida	Marsh (peat)		9.281	Happell et al. (1994)
Florida	Marsh (peat)		2.644	Happell et al. (1994)
Florida	Marsh (peat)		33.525	Happell et al. (1994)

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Table 13B.9. Nonforested Peatland Area Density Flux Factors[a]

Location	Vegetation Type	Annual Flux (CO_2 g C per m^2 per Year)	Annual Flux (CH_4 g C per m^2 per Year)	Reference
Florida	Marsh (peat)		4.163	Happell et al. (1994)
Quebec, Canada	Fen		6.225	Helbig et al. (2017)
Florida	Marsh	–44.9		Jimenez et al. (2012)
California	Young restored wetland	–368.0	53.000	Knox et al. (2015)
California	Old restored wetland	–397.0	38.700	Knox et al. (2015)
Washington	Bog		19.950	Lansdown et al. (1992)
Ontario, Canada	Fen		18.825	Lai et al. (2014)
Ontario, Canada	Fen		3.960	Lai et al. (2014)
Ontario, Canada	Fen		10.478	Lai et al. (2014)
Quebec, Canada	Bog	–60.78		Lu et al. (2017); Sulman et al. (2012); Lund et al. (2010)
Ireland	Bog	–47.78		Lu et al. (2017); Koehler et al. (2011)
Sweden	Fen	–58.0		Lu et al. (2017); Pleichel et al. (2014)
Finland	Natural fen		15.324	Nykänen et al. (1995)
Finland	Drained fen		0.132	Nykänen et al. (1995)
Minnesota	Fen	–35.3	16.300	Olsen et al. (2013)
Michigan	Bog		52.650	Shannon and White (1994)
Michigan	Bog		7.650	Shannon and White (1994)
Ontario, Canada	Marsh	–224.0	127.000	Strachan et al. (2015)
Quebec, Canada	Poor fen, control		0.032	Strack and Waddington (2007)
Quebec, Canada	Poor fen, control		39.080	Strack et al. (2004)
Quebec, Canada	Poor fen, with water table drawdown		17.564	Strack et al. (2004)
Northern Sweden	Ombrotrophic bog, hummocks		0.220	Svensson and Rosswall (1984)
Northern Sweden	Ombrotrophic bog, between hummocks		0.615	Svensson and Rosswall (1984)
Northern Sweden	Ombrotrophic bog, shallow depressions		3.381	Svensson and Rosswall (1984)
Northern Sweden	Ombrotrophic bog, deeper depressions		5.313	Svensson and Rosswall (1984)
Northern Sweden	Ombrominerotrophic		11.987	Svensson and Rosswall (1984)
Northern Sweden	Minerotrophic fen		74.163	Svensson and Rosswall (1984)
Western Canada	Bog		1.756	Turetsky et al. (2007)
North America and Europe	Bogs and fens		26.000	Turetsky et al. (2014)

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Table 13B.9. Nonforested Peatland Area Density Flux Factors[a]

Location	Vegetation Type	Annual Flux (CO_2 g C per m^2 per Year)	Annual Flux (CH_4 g C per m^2 per Year)	Reference
Minnesota	Bog		0.036	Updegraff et al. (2001)
Florida	Swamp		19.455	Villa and Mitsch (2014)
Northern England	Acidic blanket peat		0.025	Ward et al. (2007)
Maryland	*Sphagnum* bog		–0.300	Yavitt et al. (1990)
West Virginia	*Sphagnum*/ *Eriophorum* (poor fen)		1.800	Yavitt et al. (1990)
West Virginia	*Sphagnum*/Shrub (fen)		0	Yavitt et al. (1993)
West Virginia	*Polytrichum*/Shrub (fen)		0	Yavitt et al. (1993)
New York	*Typha* marsh		17.775	Yavitt (1997)
West Virginia	*Eriophorum*		14.250	Yavitt et al. (1993)
West Virginia	*Polytrichum*		11.250	Yavitt et al. (1993)
West Virginia	Shrub		1.200	Yavitt et al. (1993)
Alaska	Fen		53.66	Gorham (1991); after Crill et al. (1988)
Ontario, Canada	Mesocosms		0.510	Blodau and Moore (2003)
Quebec, Canada	Gatineau Park		0.020	Buttler et al. (1994)
Alaska	Waterlogged tundra		32.493	Derived from Sebacher et al. (1986)
Alaska	Wet meadows		10.977	Derived from Sebacher et al. (1986)
Alaska	Alpine fen		79.037	Derived from Sebacher et al. (1986)
Florida	Freshwater marsh	106.0		Malone et al. (2014)
Canada	Hummock	–39.814		Waddington et al. (1998)
Canada	Moss sedge	–148.308		Waddington et al. (1998)
Canada	Hollow	–153.285		Waddington et al. (1998)
Canada	Deep hollow	–5.972		Waddington et al. (1998)
Colorado	Fen		40.700	Chimner and Cooper (2003)

Notes

a) Key: CO_2, carbon dioxide; g, gram; C, carbon; CH_4, methane.

Table 13B.10. Mineral Soil Forest Area Density Flux Factors for Methane[a]

Vegetation (Species/Community)	Climate Zone	Location	Annual Flux CH_4 (g C per m^2 per Year)	Reference
Temperate	Temperate	Georgia	17.25	Pulliam (1993)
Dwarf cypress	Subtropical	Florida	2.025	Bartlett et al. (1989)
Swamp forest	Subtropical	Florida	18.825	Bartlett et al. (1989)
Hardwood hammock	Subtropical	Florida	0.000	Bartlett et al. (1989)
Cypress swamp, flowing water	Subtropical	Florida	18.300	Harriss and Sebacher (1981)
Cypress swamp, deep water	Subtropical	Georgia	25.200	Harriss and Sebacher (1981)
Cypress swamp, floodplain	Subtropical	South Carolina	2.700	Harriss and Sebacher (1981)
Maple/Gum forested swamp	Temperate	Virginia	0.375	Harriss et al. (1982)
Wetland forest	Temperate	Florida	16.125	Harriss et al. (1988)
Swamp forests	Temperate	Louisiana	39.825	Alford et al. (1997)
Pools forested swamp	Temperate	New York	51.750	Miller and Ghiors (1999)
Open water swamp	Subtropical	Florida	131.025	Schipper and Reddy (1994)
Waterlily slough	Subtropical	Florida	24.825	Schipper and Reddy (1994)
Lowland shrub and forested wetland	Temperate	Wisconsin	9.300	Werner et al. (2003)
Oak swamp (bank site)	Temperate	Virginia	31.950	Wilson et al. (1989)
Ash tree swamp	Temperate	Virginia	41.475	Wilson et al. (1989)

Notes

a) Key: CH_4, methane; g, gram; C, carbon.

Table 13B.11. Mineral Soil Nonforested Area Density Flux Factors[a]

Climate Zone	Location	NEE Emission (g CO_2-C per m^2 per Year)	CH_4 Emission (g CH_4-C per m^2 per Year)	Reference
Temperate	Prairie Pothole Region, Canada		4.900	Badiou et al. (2011)
Tropical	Global		41.900	Bartlett and Harriss (1993)
Temperate	Global		32.800	Bartlett and Harriss (1993)
Temperate	Ottawa, Ontario, Canada	–264.0		Bonneville et al. (2008)
Temperate	Ohio	65.4	37.650	Chu et al. (2015)
Temperate	Sanjiang Plain, China		35.100	Ding and Cai (2007)
Temperate	North Dakota		10.650	Gleason et al. (2009)
Temperate	North Florida		23.700	Happell et al. (1994)
Temperate	North Florida		7.500	Happell et al. (1994)
Tropical	South Florida		16.875	Harriss et al. (1988)
Temperate	Denmark		8.250	Herbst et al. (2011)
Tropical	Louisiana		35.100	Holm et al. (2016)
Temperate	Sanjiang Plain, China		22.500	Huang et al. (2010)
Temperate	Sanjiang Plain, China		16.875	Huang et al. (2010)
Tropical	Everglades, Florida	–44.9		Jimenez et al. (2012)
Temperate	Nebraska		60.000	Kim et al. (1999)
Temperate	Nebraska		48.000	Kim et al. (1999)
Temperate	Louisiana	–289.9	35.325	Krauss et al. (2016)
Tropical	Southwest Florida		0.600	Li and Mitsch (2016)
Tropical	Southwest Florida		92.925	Li and Mitsch (2016)
Tropical	Everglades, Florida	–40.24		Malone et al. (2014)
Temperate	North Carolina		0.525	Morse et al. (2012)
Temperate	Ohio		56.850	Nahlik and Mitsch (2010)
Temperate	Minnesota		8.775	Naiman et al. (1991)
Temperate	Minnesota		10.800	Naiman et al. (1991)
Temperate	Colorado		30.525	Neff et al. (1994)
Temperate	Virginia		54.113	Neubauer et al. (2000)
Temperate	Saskatchewan, Canada		24.100	Pennock et al. (2010)
Temperate	Saskatchewan, Canada		26.175	Pennock et al. (2010)
Temperate	Saskatchewan, Canada		18.075	Pennock et al. (2010)
Boreal	Saskatchewan, Canada		10.875	Rask et al. (2002)
Tropical	Everglades, Florida	–49.9		Schedlbauer et al. (2010)
Temperate	Georgia	92.4		Segarra et al. (2013)
Temperate	Minnesota		14.600	Shurpali and Verma (1998)
Temperate	Colorado		7.725	Smith and Lewis (1992)
Temperate	Sanjiang Plain, China		21.675	Song et al. (2003)
Temperate	Sanjiang Plain, China		32.550	Song et al. (2003)

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Table 13B.11. Mineral Soil Nonforested Area Density Flux Factors[a]

Climate Zone	Location	NEE Emission (g CO_2-C per m² per Year)	CH_4 Emission (g CH_4-C per m² per Year)	Reference
Temperate	Sanjiang Plain, China		4.350	Song et al. (2009)
Temperate	Sanjiang Plain, China		0.225	Song et al. (2009)
Temperate	Ottawa, Ontario, Canada	–223.8	127.000	Strachan et al. (2015)
Tropical	Everglades, Florida		39.975	Villa et al. (2014)
Temperate	Colorado		31.275	Wickland et al. (1999)
Temperate	Colorado		23.456	Wickland et al. (1999)
Temperate	Virginia		31.725	Wilson et al. (1989)
Temperate	Virginia		16.988	Wilson et al. (1989)
Temperate	Three Gorges Reservoir, China		0.975	Yang et al. (2012)
Temperate	New York		93.975	Yavitt et al. (1997)
Temperate	New York		13.331	Yavitt et al. (1997)
Temperate	New York		41.906	Yavitt et al. (1997)
Temperate	Maryland and West Virginia		0.281	Yavitt et al. (1990)
Temperate	New York		10.688	Yavitt et al. (1993)
Temperate	New York		8.438	Yavitt et al. (1993)
Temperate	New York		0.900	Yavitt et al. (1993)
Temperate	Czech Republic	–126.3		Lu et al. (2017); Marek et al. (2011)
Boreal	Quebec, Canada	–264.0		Lu et al. (2017); Bonneville et al. (2008)
Boreal	Finland	–37.0		Lu et al. (2017); Lund et al. (2010)
Temperate	China	–61.67		Lu et al. (2017); Yu et al. (2013)
Temperate	Wisconsin	–83.99		Lu et al. (2017); Sulman et al. (2009)

Notes

a) Key: NEE, net ecosystem exchange; CO_2, carbon dioxide; CH_4, methane; g, gram; C, carbon.

14 Inland Waters

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KEY FINDINGS

1. The total flux of carbon—which includes gaseous emissions, lateral flux, and burial—from inland waters across the conterminous United States (CONUS) and Alaska is 193 teragrams of carbon (Tg C) per year. The dominant pathway for carbon movement out of inland waters is the emission of carbon dioxide gas across water surfaces of streams, rivers, and lakes (110.1 Tg C per year), a flux not identified in the *First State of the Carbon Cycle Report* (SOCCR1; CCSP 2007). Second to gaseous emissions are the lateral fluxes of carbon through rivers to coastal environments (59.8 Tg C per year). Total carbon burial in lakes and reservoirs represents the smallest flux for CONUS and Alaska (22.5 Tg C per year) (*medium confidence*).

2. Based on estimates presented herein, the carbon flux from inland waters is now understood to be four times larger than estimates presented in SOCCR1. The total flux of carbon from inland waters across North America is estimated to be 507 Tg C per year based on a modeling approach that integrates high-resolution U.S. data and continental-scale estimates of water area, discharge, and carbon emissions. This estimate represents a weighted average of 24 grams of carbon per m^2 per year of continental area exported and removed through inland waters in North America (*low confidence*).

3. Future research can address critical knowledge gaps and uncertainties related to inland water carbon fluxes. This chapter, for example, does not include methane emissions, which cannot be calculated as precisely as other carbon fluxes because of significant data gaps. Key to reducing uncertainties in estimated carbon fluxes is increased temporal resolution of carbon concentration and discharge sampling to provide better representations of storms and other extreme events for estimates of total inland water carbon fluxes. Improved spatial resolution of sampling also could potentially highlight anthropogenic influences on the quantity and quality of carbon fluxes in inland waters and provide information for land-use planning and management of water resources. Finally, uncertainties could likely be reduced if the community of scientists working in inland waters establishes and adopts standard measurement techniques and protocols similar to those maintained through collaborative efforts of the International Ocean Carbon Coordination Project and relevant governmental agencies from participating nations.

Note: Confidence levels are provided as appropriate for quantitative, but not qualitative, Key Findings and statements.

14.1 Introduction: The Aquatic Carbon Cycle

14.1.1 Inland Waters in the Carbon Cycle

This chapter provides an assessment of the total mass of carbon moving from terrestrial ecosystems into inland waters and places this flux in the context of major carbon loss pathways. Also provided is evidence that the estimated carbon flux through inland waters is poorly constrained, highlighting several opportunities to improve future estimates of carbon flows through aquatic ecosystems. Inland waters are defined in this chapter as open-water systems of lakes, reservoirs, nontidal rivers, and streams (see Ch. 13: Terrestrial Wetlands, p. 507, and Ch. 15: Tidal Wetlands and Estuaries, p. 596, for assessments of those ecosystems). Carbon within inland waters includes dissolved and particulate species of inorganic and organic carbon. The separation between dissolved and particulate carbon is operational and reflects, in general, a filtration through a 0.2- to 0.7-micrometer (μm) filter, where the larger material is considered particulate within freshwater environments. Using this definition classifies inland water carbon as dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), particulate organic carbon (POC), and particulate inorganic carbon (PIC). Included within the DIC pool is dissolved carbon dioxide (CO_2).

Lakes, ponds, streams, rivers, and reservoirs are both the intermediate environments that transport,

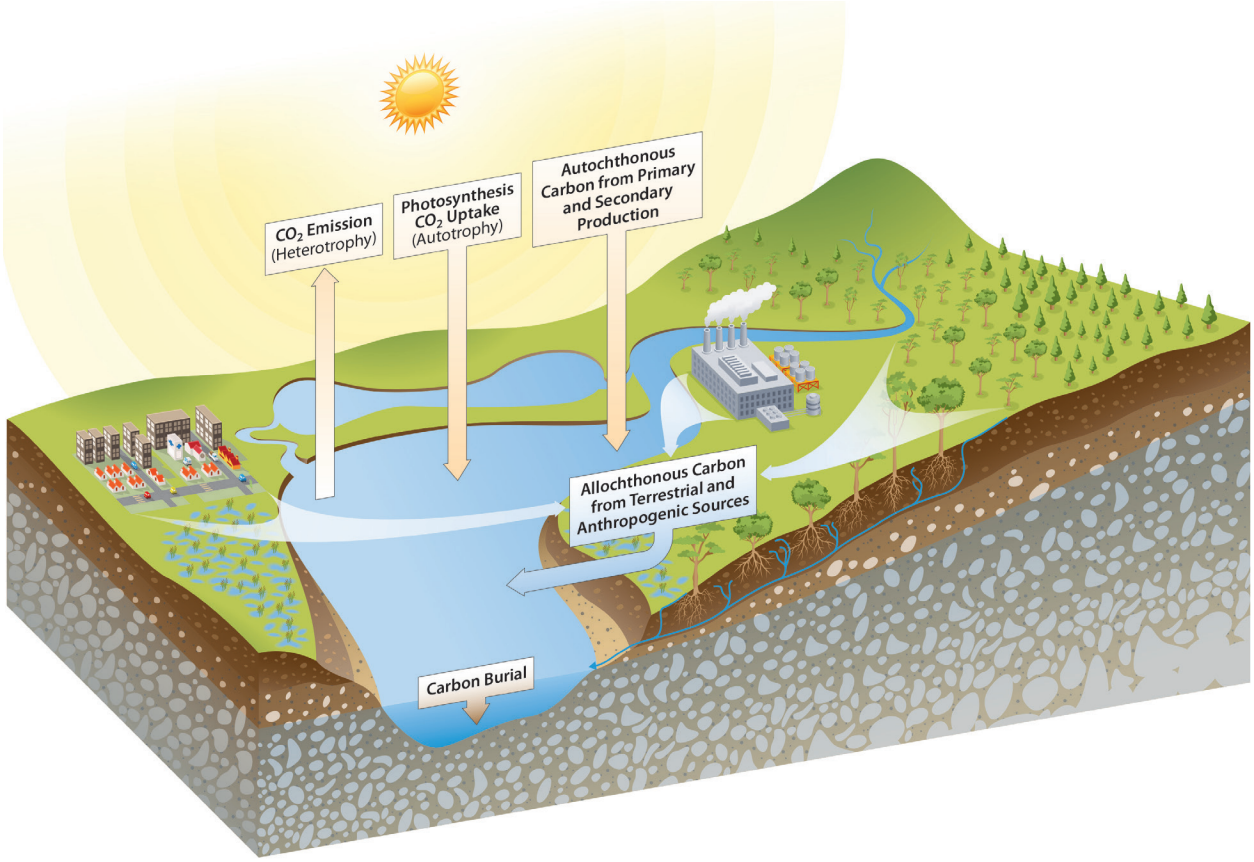

Figure 14.1. Carbon Flux Pathways in Aquatic Environments. Allochthonous carbon represents organic and inorganic carbon, including dissolved carbon dioxide (CO_2), that enters aquatic environments from terrestrial systems. Autochthonous carbon originates from primary and secondary production that uses either atmospheric CO_2 or dissolved inorganic carbon from the aquatic environment. Primary production within autotrophic systems is responsible for the net uptake of atmospheric CO_2, while respiration and allochthonous inputs of carbon within a heterotrophic system are responsible for a net CO_2 emission to the atmosphere. Burial represents the deposition of autochthonous and allochthonous particulate carbon.

sequester, and transform carbon before it reaches coastal environments (Liu et al., 2010) and dynamic ecosystems that sustain primary and secondary production supporting aquatic metabolism and complex food webs. Inland waters comprise a small fraction of Earth's surface yet play a critical role in the global carbon cycle (Battin et al., 2009b; Butman et al., 2016; Cole et al., 2007; Findlay and Sinsabaugh 2003; Regnier et al., 2013; Tranvik et al., 2009). Over geological timescales, inland waters control long-term sequestration of atmospheric CO_2 through the hydrological transport of inorganic carbon from terrestrial weathering reactions to coastal and marine carbon "sinks" as dissolved carbonate species (Berner 2004). Today, through anthropogenic land-use change, industrialization, damming, and changes in climate, the ecosystem structure and function of inland waters are changing rapidly. However, as presented in this chapter, the flows of carbon through inland waters represent a combination of both natural and anthropogenic influences, (see Figure 14.1, this page) as the science has not achieved a comprehensive ability to differentiate anthropogenic fluxes from natural fluxes. In the context of the North

American carbon cycle, the science discussed herein addresses current understanding of freshwater carbon cycling from the period since 1990 and highlights the need to focus on better identifying human impacts on the transport and biogeochemical cycling of carbon by inland waters.

14.1.2 Defining Carbon Within Inland Waters

Inland aquatic ecosystems are sites for biogeochemical carbon reactions that result in an exchange of particulate and dissolved carbon, CO_2, and methane (CH_4) among aquatic environments, terrestrial environments, and the atmosphere (Butman and Raymond 2011; Findlay and Sinsabaugh 2003; McCallister and del Giorgio 2012; McDonald et al., 2013; Raymond et al., 2013; Striegl et al., 2012). Carbon species in freshwaters originate from varied sources. Aquatic organic carbon consists of all organic molecules transported to or produced within inland waters and their various organic decomposition products. Inland water organic carbon originates from direct inputs from wastewater, surface runoff (typically, the largest contributor), groundwater, primary and secondary production within the aquatic environment, and atmospheric deposition. Inorganic carbon includes PIC and DIC. The mass balance of DIC in freshwater ecosystems is regulated by biological processes such as photosynthesis (consuming CO_2) and respiration (producing CO_2), along with air-water CO_2 exchange and geochemical reactions, including carbonate precipitation and dissolution (Tobias and Bohlke 2011).

Rivers are conduits that deliver carbon to the coast while maintaining strong CO_2 and CH_4 fluxes to or from the atmosphere (Cole et al., 2007; Stanley et al., 2016; Tranvik et al., 2009). Lakes and reservoirs are sinks of particulate carbon in sediments and also process and remineralize organic carbon to CO_2 and CH_4 gases that are then emitted to the atmosphere (Clow et al., 2015; Teodoru et al., 2012). Autotrophic carbon production in nutrient-enriched lakes and reservoirs can cause inland water bodies to be a sink of atmospheric CO_2 (Clow et al., 2015; Tranvik et al., 2009). The entrapment of sediments by dams can facilitate aerobic and anaerobic organic carbon oxidation and thus the net production of CO_2 and CH_4 that escape to the atmosphere, with important implications to climate forcing (Crawford and Stanley 2016; Deemer et al., 2016). However, the balances among primary production, total respiration, carbon burial, and carbon gas emission in lakes and reservoirs remain poorly quantified (Arntzen et al., 2013; Teodoru et al., 2012).

Of the roughly 2.9 petagrams of carbon (Pg C) per year that enter inland waters globally, most are emitted as CO_2 across the air-water interface (Butman et al., 2016; Raymond et al., 2013) before ever reaching the ocean (Le Quéré et al., 2014). Recent estimates suggest that inland water surface carbon emissions may exceed 2 Pg C per year (Sawakuchi et al., 2017). In contrast, rivers export to the coastal ocean 0.4 Pg C per year of DIC and between 0.2 and 0.43 Pg C per year of organic carbon (Le Quéré et al., 2014; Ludwig et al., 1996; Raymond et al., 2013; Schlünz and Schneider 2000). However, the biogeochemical processes that produce and sustain both atmospheric carbon emissions and lateral fluxes remain unclear because physical and biological processes vary significantly across freshwater systems and along the hydrological continuum (see Figure 14.2, p. 572; Battin et al., 2008; Hotchkiss et al., 2015).

Carbon fluxes in inland waters are considered in Equation 14.1 in the context of a simple mass balance approach.

Equation 14.1

$$C_{aquatic} = C_{allochthonous} - [C_{emissions} + C_{burial} + C_{export}]$$

The dimensions of this equation are mass carbon (C) per unit time (e.g., Tg C per year) or mass C per unit area per unit time (e.g., units of g C per m^2 per year), where $C_{aquatic}$ represents the change of carbon stock in inland waters, $C_{allochthonous}$ is the input of allochthonous carbon into inland waters from land, $C_{emissions}$ is the total emissions of CO_2 and CH_4 from the water surface, C_{burial} is the total burial of POC in lakes and reservoirs, and C_{export} is

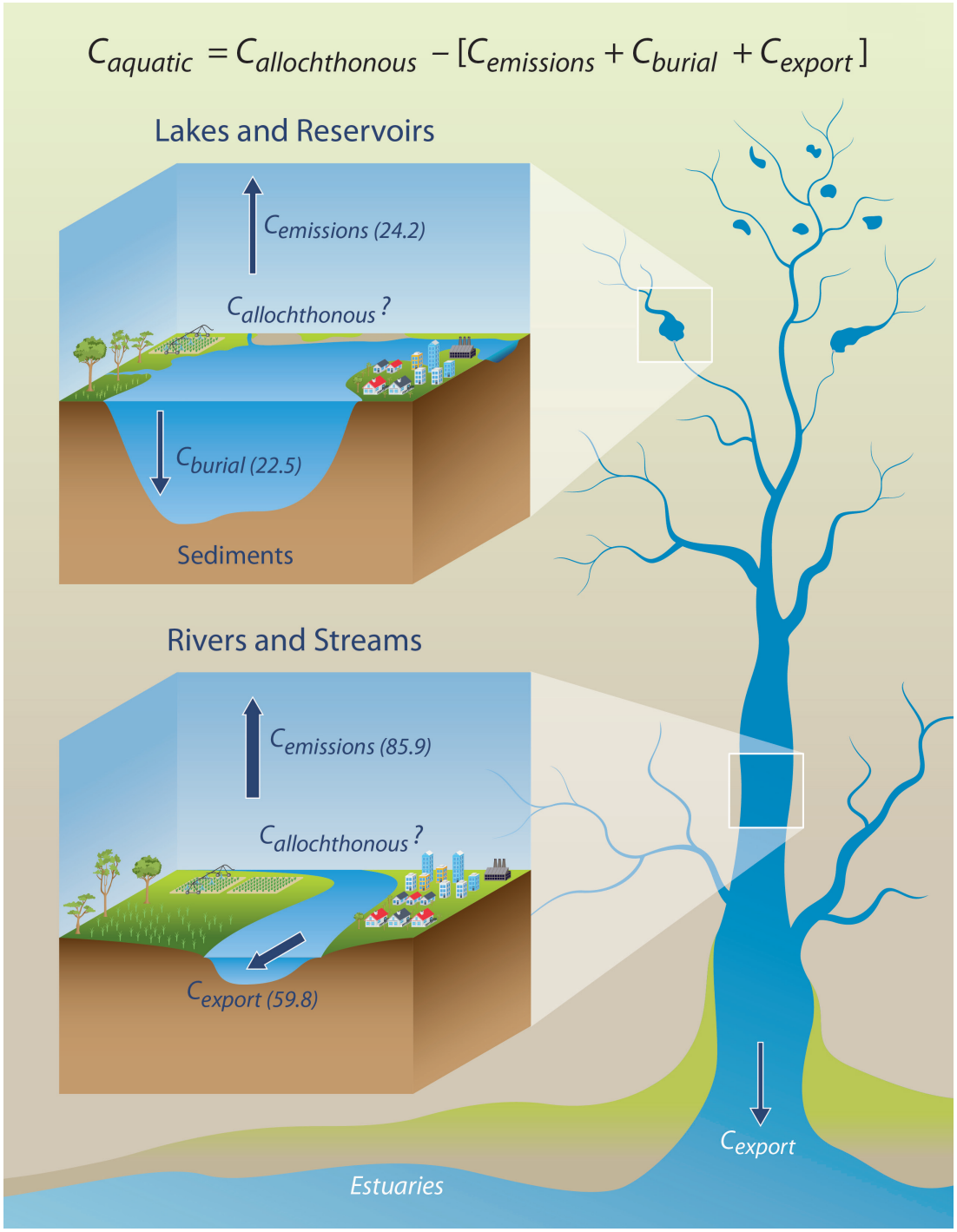

Figure 14.2. Carbon Fluxes from Inland Waters of the Conterminous United States and Alaska. All values represent total fluxes in teragrams of carbon (Tg C) per year. River fluxes represent total carbon fluxes to the point of the head of tide, or the highest flow gaging station not influenced by tidal movement. Individual fluxes from different land uses are not quantified but represented by the mass balance of all aquatic carbon fluxes. The total flux (see Equation 14.1, p. 571) is 193 Tg C per year. Further information regarding estimates of uncertainty are presented in Stackpoole et al. (2017a) and Butman et al. (2016).

the total export of inorganic and organic carbon to coastal systems. For this analysis, estimates of CH_4 emissions are not provided. Furthermore, changes in carbon stocks are assumed to be zero (i.e., assumption of steady state), which is reasonable over long timescales because of the rapid movement and turnover of carbon in lotic (flowing) and lentic (still) ecosystems. Hence, in this chapter, the flux of carbon from inland waters (the terms within brackets in Equation 14.1, p. 571) is assumed to be equivalent to the flux of carbon to inland waters, $C_{terrestrial}$. The use of this equation implies a fully constrained hydrological system. Adjustments have been made to U.S. flux estimates for carbon originating outside national boundaries.

14.1.3 Inland Waters of the United States and North America

The conterminous United States (CONUS) and Alaska contain over 45 million individual lakes and ponds greater than 0.001 km^2. Excluding the Laurentian Great Lakes (see Section 14.1.4, p. 574), these lakes and ponds cover an estimated 179,000 to 183,000 km^2 (Butman et al., 2016; Clow et al., 2015; McDonald et al., 2012; Zhu and McGuire 2016) and include more than 87,000 reservoir systems (Clow et al., 2015; Hadjerioua et al., 2012). Streams and rivers in the United States and Alaska are estimated to cover 36,722 km^2 (Butman et al., 2016; Stackpoole et al., 2017b; Zhu and McGuire 2016). Combined, inland waters (except the Great Lakes) cover approximately 1.9% of CONUS and 3.9% of Alaska. Although 30-m resolution map products include inland freshwater bodies >0.005 km^2 (Feng et al., 2015), large-scale water-surface map products currently do not capture smaller-scale water bodies (<0.001 km^2), which have been linked with higher greenhouse gas (GHG) emissions rates (Holgerson and Raymond 2016). All stream and river areas in this chapter are estimated by scaling the relationships among discharge and water velocity, water depth, and stream or river width (Melching and Flores 1999; Raymond et al., 2012). Freshwater discharge to the coast of North America is dominated by the Mississippi, St. Lawrence, Mackenzie, Columbia, and Yukon rivers, which have a combined discharge of 1,500 km^3 per year, about half the total freshwater runoff to the coast of North America (Dai et al., 2009).

The boreal area of North America constitutes one of the most lake-rich regions in the world. In Canada alone, there are an estimated 3.3 million water bodies greater than 0.01 km^2 in surface area and another 5.4 million in the smallest size category (<0.001 km^2). All Canadian water bodies (excluding the Great Lakes) are estimated to cover 884,000 km^2, or about 9% of the country's surface. In some large regions of northern Quebec and Ontario, inland waters cover up to 25% of the surface area. In Mexico, surface waters (excluding fluvial systems) are estimated to cover 25,769 km^2, or 1% of the country's surface, and the total length of streams and rivers is estimated to be 633,000 km (INEGI 2017). The watersheds of Mexico's 33 main rivers cover 565,128 km^2, and freshwater flow is dominated by the Grijalva and Usumancinta rivers, which drain to the Gulf of Mexico.

There are 87,359 registered dams in the United States (USACE 2016), more than 10,000 dams in Canada (Canadian Dam Association 2018), and 5,163 dams and reservoirs holding approximately 150 km^3 of water in Mexico (CONAGUA 2015). Dam construction in recent years has increased the volume of retained water by about 600% to 700% globally, tripling the transit time of water from land to sea (Vörösmarty et al., 2009). This trend is expected to continue globally with several large damming projects underway (Zarfl et al., 2014). Within the United States, nearly 2,500 dams provide 78 gigawatts (GW) of power; up to 12 GW potentially could be added by leveraging the installed dam capacity currently not being used for energy production (Hadjerioua et al., 2012). The U.S. Pacific Northwest and Southeast have the highest potential for future power generation (Hadjerioua et al., 2012). Reservoirs formed through the damming of rivers alter the natural flux of carbon and the dispersal of sediments (Dean and Gorham 1998), increasing the likelihood that organic carbon will be

remineralized to CH_4 and CO_2 compared to unrestricted conditions (Deemer et al., 2016; Rudd et al., 1993; Teodoru et al., 2012). Thus, the conversion of meandering rivers to a series of reservoirs potentially reduces the transport of carbon to the coast (Hedges et al., 1997), and it may increase the flux of CO_2 and CH_4 to the atmosphere (Deemer et al., 2016; Tranvik et al., 2009; Tremblay et al., 2005).

14.1.4 The Great Lakes

The Laurentian Great Lakes vary between being considered as part of the coastal domain or as inland waters because each of the five lakes is distinct in size and volume. In this chapter, these lakes are considered as inland waters, containing about 18% of the world's supply of surface fresh liquid water and 84% of North America's supply (www.epa.gov/greatlakes/great-lakes-facts-and-figures). Although interconnected, the lakes differ substantially in their physical, biological, and chemical characteristics. The largest, Lake Superior, has an average depth of 147 m and a water retention time of nearly 200 years, while the smallest, Lake Erie, has an average depth of 19 m and a retention time of about 3 years. Productivity ranges from oligotrophic in Lake Superior to eutrophic in Lake Erie. Water chemistry also varies substantially among the lakes, with mean alkalinity ranging from 840 micromoles (μmol) per kg in Lake Superior to 2,181 μmol per kg in Lake Michigan (Phillips et al., 2015).

Despite the large size of the Great Lakes, knowledge of their lakewide carbon cycle is relatively limited. Recent observational and modeling studies have helped elucidate some of the physical and biogeochemical processes governing the seasonal carbon cycle (Atilla et al., 2011; Bennington et al., 2012; Pilcher et al., 2015), but current CO_2 emissions estimates are poorly constrained and are excluded from regional carbon budgets (McDonald et al., 2013). Observations of surface partial pressure of CO_2 (pCO_2) suggest that the Great Lakes are in near equilibrium with the atmosphere on annual timescales but vary seasonally between periods of significant undersaturation and supersaturation (Atilla et al., 2011; Karim et al., 2011; Shao et al., 2015). Autochthonous carbon from spring and summer productivity is respired at depth and ventilated back to the atmosphere during strong vertical mixing in late fall and winter, limiting burial (Pilcher et al., 2015). However, even highly productive regions, such as western Lake Erie, have been shown to be net sources of carbon to the atmosphere (Shao et al., 2015). Additional data are required to better understand the lakewide response to increasing atmospheric CO_2 and any resulting, decreasing trend in lake pH (Phillips et al., 2015). Further uncertainty arises from a long history of anthropogenic stressors that have significantly affected lakewide ecology and ecosystem services (Allan et al., 2013). A recent example is the proliferation of invasive *Dreissena* mussels throughout most of the Great Lakes. Filter feeding from these mussels coincides with substantial reductions in aquatic primary productivity, which probably has altered the lakewide food web and resulted in unknown impacts to the carbon cycle (Evans et al., 2011; Madenjian et al., 2010).

14.2 Historical Context

14.2.1 Early Understandings

The study of carbon cycling in lakes, streams, and large rivers started in the early part of the last century with the development of the ecosystem concept as a functional unit by which scientists could define the physical, chemical, and biological structure of the world around them. This concept was adapted from terrestrial to aquatic systems through seminal work (Lindeman 1942) partitioning the movement of energy, and as a result carbon, across trophic levels in lakes. A second concept relevant to carbon cycling in inland waters is the tracing of elements through natural systems, which has a long history in geochemistry and had developed prior to the notion of ecology. The convergence of these two concepts that define the interactions among biological, physical, and chemical environments was permanently established by the need to 1) improve water quality from eutrophication of freshwaters by agricultural fertilizer inputs and 2) understand the impacts of acid rain through the exploration of elemental cycling in whole lakes (Johnson and

Vallentyne 1971) and at the watershed scale (Likens 1977). Although carbon remained secondary to the tracing of nutrients and other chemical species, research clearly established that carbon from terrestrial systems provided energy to and influenced the structure of aquatic systems (Pace et al., 2004) and that the boundary between these two systems might not be so discrete. A rich field of ecosystem-based science subsequently developed that expanded dramatically into this century. In an attempt to synthesize carbon dynamics in freshwaters, a group through the National Center for Ecological Analysis and Synthesis produced a seminal paper that highlighted the magnitude of the flows of carbon through freshwaters at the global scale (Cole et al., 2007), laying the foundation for the research that supports this chapter.

14.2.2 *First State of the Carbon Cycle Report*

The *First State of the Carbon Cycle Report* (SOCCR1) identified rivers and lakes as a net sink of 25 Tg C per year into sediments across North America (CCSP 2007; Pacala et al., 2001; Stallard 1998). The total lateral transfer of carbon (including both DIC and DOC) to the ocean was estimated to be 35 Tg C per year (Pacala et al., 2001) and was considered highly uncertain. These estimates did not include Canada, Mexico, or the Great Lakes because of a lack of available data for each. It is important to note that all estimates for rivers were considered sinks or net transfers of carbon to the coastal environment, as well as storage of carbon in lake and reservoir sediments. Since 2007, the research community has widely accepted that inland aquatic ecosystems also function as an important interface for carbon exchange between terrestrial ecosystems and the atmosphere (Cole et al., 2007; Tranvik et al., 2009). Evidence summarized herein shows that, over short timescales, freshwaters function as sources of atmospheric CO_2. Also provided are improved estimates of burial in lakes and reservoirs and lateral transfer to the coast. The updated budget increases the total carbon fluxes from inland waters by a factor of two over those reported in SOCCR1 (see Table 14.1, p. 576) and alters the previous perception of inland waters as a sink of atmospheric CO_2. These estimates of inland water fluxes, coupled with a better understanding of flow paths for carbon losses and export from wetland and coastal environments, provide evidence that the majority of terrestrially derived carbon moving through inland waters is released to the atmosphere as CO_2.

14.3 Current Understanding of Carbon Fluxes and Stocks

A more complete accounting of aquatic carbon has been a major advance in aquatic carbon cycle science, specifically the inclusion of CO_2 emissions from rivers and lakes to the atmosphere. Additionally, publications of high-resolution inventories of lake and river surface areas have enabled researchers to more accurately scale up local hydrology and chemistry datasets to regional and continental scales. One of the most important results from these new and rigorous assessments is the documentation of regional variability across Arctic, boreal, temperate, subtropical, and tropical ecosystems in North America.

14.3.1 Carbon Fluxes from U.S. Waters

Contemporary total inland water carbon fluxes from CONUS and Alaska were estimated with comparable datasets and methodologies (Butman et al., 2016; Stackpoole et al., 2016). Total aquatic carbon fluxes represent the sum of 1) lateral transport of DIC and total organic carbon (TOC) from river systems to the coast, 2) CO_2 emissions from rivers and lakes, and 3) carbon burial in sediments. Although burial in lake sediments also has been considered storage at the continental scale, this report considers burial as the removal of carbon from the aqueous environment and thus adds burial to the total flux (see Equation 14.1, p. 571).

The estimated total carbon flux from inland waters in CONUS is 147 Tg C per year (5% and 95%: 80.5 and 219 Tg C presented in Butman et. al., 2016). In Alaska, it is 44.5 Tg C per year (31.4 and 52.5 Tg C presented in Stackpoole et al., 2016). These

Table 14.1. U.S., North American, and Global Annual Carbon Fluxes from Inland Waters[a–k]

Source	United States[a]	Canada	Mexico	Great Lakes	North America	Globe (Pg C per Year)
	(Tg C per Year)					
Rivers and Streams						
Lateral Fluxes	59.8***	18.2 (TOC)[b]	ND	ND	105****	0.6–0.7[c]
Gas Emissions	85.9**	ND	ND	ND	124.5**	0.7–1.8[d] (2.9)[e]
Lakes and Reservoirs						
Burial	22.5**	ND	ND	2.7*[h]	155**	0.2–0.6[f]
Gas Emissions	24.2***	ND	ND	ND	122**	0.6[g]
Inland Aquatic Systems						
Total Carbon Flux	193***	ND	ND	2.3–36*[i]	507**	2.1–3.7 (4.9)
Net Carbon Yield (g C per m^2 per year)	20.6***	ND	ND	ND	23.2**	16–17 (33)

Notes

a) Butman et al. (2016); Stackpoole et al. (2016). United States includes the conterminous United States and Alaska.

b) Clair et al. (2013).

c) Dai et al. (2012); Meybeck (1982); Seitzinger et al. (2005); Hartmann et al. (2014b); Spitzy and Ittekkot (1991); Syvitski and Milliman (2007); Galy et al. (2015).

d) Raymond et al. (2013); Lauerwald et al. (2015).

e) All estimates in parenthesis derived from Sawakuchi et al. (2017).

f) Battin et al. (2009a); Tranvik et al. (2009).

g) Aufdenkampe et al. (2011).

h) Einsele et al. (2001).

i) McKinley et al. (2011).

j) All fluxes include inorganic and organic carbon as well as particulate and dissolved species.

k) Key: Tg C, teragrams of carbon; Pg C, petagrams of carbon; g C, grams of carbon; TOC, total organic carbon; ND, no data; Asterisks indicate that there is 95% confidence that the actual value is within 10% (*****), 25% (****), 50% (***), 100% (**), or >100% (*) of the reported value.

estimates combine for a total flux of about 193 Tg C per year, as presented in Table 14.1, this page. Carbon yields, which represent fluxes normalized by land surface area, are 18.6 g C per m^2 per year in CONUS and 29 g C per m^2 per year in Alaska. The higher value for Alaska is most likely related to the higher water surface area found across the state. Combined and weighted by area, the average yield for CONUS and Alaska is 20.6 g C per m^2 per year.

Rivers dominate total carbon fluxes from inland waters in CONUS and Alaska. Coastal carbon export is 41.5 Tg C per year (5% and 95%: 39.4, 43.5 Tg C) for CONUS and 18.3 Tg C per year (16.3, 25.0 Tg C) for Alaska. River CO_2 emissions are 69.3 Tg C per year (36.0, 109.6 Tg C) and 16.6 Tg C per year (9.0, 26.3 Tg C), respectively.

Carbon burial in lakes and reservoirs is 20.6 Tg C per year (9.0, 65.1 Tg C) in CONUS and 1.9 Tg C per year (1.3, 2.8 Tg C) in Alaska, lower than the respective river fluxes to the coast. Lake emissions are 16.0 Tg C per year (14.3, 18.7 Tg C) in CONUS and 8.2 Tg C per year (6.1, 11.2 Tg C) in Alaska. Lake CO_2 losses to the atmosphere roughly equal the magnitude of carbon buried in lake sediments in CONUS, but lake CO_2 emissions are much greater relative to carbon burial rates in Alaska.

14.3.2 Carbon Fluxes from Canadian Waters

The Canadian climate and terrestrial landscape are highly heterogeneous, from temperate rainforests to Arctic desert. The transport and processing of carbon in Canada's inland waters are correspondingly variable. Although lake or river carbon cycling has been studied in several regions, significant gaps remain in this report's assessment of country-wide carbon transport and transformation in aquatic systems. The terrestrial carbon export rate to aquatic networks varies from <1 g C per m^2 per year to >20 g C per m^2 per year for both organic and inorganic fractions, though their relative importance is region- specific (Clair et al., 2013). A recent estimate for all the drainage basins in Canada suggests that 18.2 Tg of organic carbon is exported to the coast each year (Clair et al., 2013). Although DIC is the dominant form of carbon export from terrestrial systems in the Prairie provinces, Manitoba, Saskatchewan, and Alberta (Finlay et al., 2010), the balance shifts toward co-equality in Southern Quebec catchments (Li et al., 2015) and to a dominance of organic carbon in the boreal zone (Molot and Dillon 1997; Roulet and Moore 2006). The combined organic and inorganic lateral flux from land to the coast is currently unavailable.

While the vast majority of Canadian lakes and rivers are supersaturated in CO_2 and CH_4 relative to the atmosphere and thus act as sources (Campeau et al., 2014; del Giorgio et al., 1997; Prairie et al., 2002; Teodoru et al., 2009), alkaline and eutrophic systems can act, at least temporarily, as carbon sinks (Finlay et al., 2010). Generally, however, Canadian lakes are net heterotrophic through the degradation of incoming DOC (Vachon et al., 2016), with emission rates of CO_2 and CH_4 from lakes typically varying as an inverse function of lake size (Rasilo et al., 2015; Roehm et al., 2009) and positively with organic matter inputs (del Giorgio et al., 1999). Lakes of northern Quebec have accumulated more carbon per unit area than their surrounding forest soils but less than surrounding peatlands (Heathcote et al., 2015). Lake bathymetric shape and exposure to oxygen are the primary determinants of carbon accumulation and of the efficiency of burial relative to the carbon supply (Ferland et al., 2014; Teodoru et al., 2012). At the whole-landscape scale, lake sediments account for about 15% of the accumulated carbon (Ferland et al., 2012).

14.3.3 Carbon Fluxes from Mexican Waters

Extensive data on carbon stocks and fluxes do not yet exist for Mexico, but a summary exists of several individual small-scale datasets about Mexican inland water carbon fluxes (Alcocer and Bernal-Brooks 2010). The state of knowledge presented herein regarding carbon cycling in the inland waters of Mexico focuses on lake GHG emissions and burial. Given the tectonic activity of Mexico, there has been an interest in understanding how the carbon emissions of volcanic lakes evolve across space and time. Carbon dioxide emissions from the lake inside El Chichón volcano, Chiapas, reportedly range from 0.005 to 0.016 Tg C per year, or 72,000 to 150,000 g C per m^2 per year (Mazot and Taran 2009; Perez et al., 2011). More recently, research on Lake Alchichica showed that, on average, surface water pCO_2 was below atmospheric pCO_2 for 67% of the year, with an average surface water pCO_2 of 184 microatmospheres (µatm; Guzmán-Arias et al., 2015). These findings suggest that deep, tropical, and warm monomictic lakes have the potential to take up atmospheric CO_2 through primary production and preserve most of the POC deposited to the sediments, creating important carbon sinks. Emissions of CH_4 may be as important as emissions of CO_2 across regions of Mexico. Although few studies have evaluated the CH_4 emissions from Mexican inland waters, the CH_4 flux from six Mexican lakes is estimated to be about 1.3 ± 0.4 Tg CH_4 per year, which constitutes 20% of Mexico's CH_4 emissions (Gonzalez-Valencia et al., 2013). The total CH_4 flux from 11 aquatic ecosystems in Mexico City was 0.004 Tg CH_4 per year, 3.5% of the CH_4 emissions of the city (Martinez-Cruz et al., 2016). Fully quantifying the importance of anthropogenic inputs of CH_4-producing organic materials through waste

streams is critical for better constraining these fluxes at the national scale.

Other research on inland water carbon dynamics in Mexico has focused on reservoirs. The CO_2 emissions of the Valle de Bravo reservoir, Estado de Mexico, calculated through the photosynthesis and respiration balance, was 0.34 g C per m^2 per year (Valdespino-Castillo et al., 2014). Carbon burial has been studied in a few Mexican lakes. A 3-year study determined that the well-characterized system of Lake Alchichica, Puebla, has a carbon burial rate of 25.6 ± 12.3 g C per m^2 per year (Oseguera-Pérez et al., 2013).

14.3.4 Carbon Fluxes from the Great Lakes

As previously suggested, a comprehensive assessment of carbon fluxes does not yet exist for all of the Laurentian Great Lakes. The best estimates for individual component carbon flux values for the Great Lakes come from Lake Superior. Primary production is estimated to be 5.3 to 9.7 Tg C per year, while respiration is estimated to be significantly greater at 13 to 83 Tg C per year (Cotner et al., 2004; Sterner 2010; Urban et al., 2005). External inputs of 0.68 to 1.03 Tg C per year (Cotner et al., 2004) of organic carbon are too small to account for this imbalance between primary production and respiration, suggesting significant sources of external DIC. However, modeling work suggests that previous respiration estimates were biased high because of spatial heterogeneity and found a much lower value of 5.5 Tg C per year (Bennington et al., 2012). Estimates do not yet exist for the balance between the amount of organic carbon buried in sediments versus the amount exported through rivers or emitted as CO_2 and CH_4. However, total carbon burial across all lakes may be on the order of 2.7 Tg C per year, with an areal sink of 15 g C per m^2 per year since 1930 (Einsele et al., 2001). Additional research is needed to constrain the fluxes of carbon from the Great Lakes.

14.4 Current and Future Trends

Whether carbon fluxes from inland waters are increasing or decreasing at the national or continental scale remains unclear. Because carbon export from the terrestrial landscape is tightly linked to discharge, increases in discharge probably will lead to increases in carbon export (Mulholland and Kuenzler 1979). Current studies are arguing for an increase in discharge for many regions of North America, including the U.S. Midwest and New England; however, reductions in precipitation are predicted in the southern and western regions of the United States (Georgakakos et al., 2014). Human water use through irrigation also may be affecting the spatial variability of discharge, with lower discharge in regions of higher irrigation, an effect which may be mitigated by increases in precipitation (Kustu et al., 2011). However, future changes in precipitation that lead to regional drought will reduce the transfer of carbon from the terrestrial ecosystem into the aquatic environment, while simultaneously decreasing the total area of aquatic ecosystems. Other anthropogenic drivers also can impact fluxes. Evidence suggests that DIC fluxes have increased from the Mississippi River over time because of land-management practices associated with liming and irrigation for agriculture, as well as increases in precipitation across portions of the basin (Raymond et al., 2008; Tian et al., 2015). In the United Sates, about 30 Tg of lime are applied each year, resulting in a potential flux of 7.2 Tg of inorganic carbon per year in the form of bicarbonate, or an actual flux of approximately 5.4 Tg C per year, assuming that 25% is balanced by the export of products from weathering reactions other than carbonic acid (Oh and Raymond 2006). The total U.S. riverine flux of DIC is approximately 35 Tg per year (Stets and Striegl 2012). Thus, liming and fertilizer use may contribute about 15% of total river bicarbonate flux in the United States.

Calculations suggest that DOC export from the Mississippi River has increased since the early 1900s, primarily a result of land-cover change from forest and grasslands to managed agriculture (Ren et al., 2016). Tributaries to the Mississippi have been shown to have decreasing DOC as a result of wetland loss (Duan et al., 2017). However, DOC flux from the Mississippi River to the

Gulf of Mexico did not change from 1997 to 2013 (Stackpoole et al., 2016). Changing concentrations of dissolved CO_2 were identified in nine lakes in the Adirondacks, New York, where six showed significant increases and three showed significant decreases over 18 years (Seekell and Gudasz 2016). The rate of change in both the positive and negative direction was found to be in excess of 12 μatm per year, well outside the rate of increase in the atmosphere. Increasing trends in these lakes were attributed first to basin-scale recovery from acid precipitation, resulting in an increase in soil CO_2 production in systems with little buffering capacity, where CO_2 can be a large contributor of inorganic carbon exported from the catchment. Also attributed were changes in DOC concentrations, export, and remineralization rates within the lake environment (Burns et al., 2006; Seekell and Gudasz 2016). Globally, evidence indicates increases in the concentrations of organic carbon from a number of sources, a phenomenon termed the "browning" of waters. However, studies suggest that these increases are caused by regionally specific factors, including recovery from acid rain; increases in carbon export from soils; and the mobilization of permafrost carbon into stream systems (Evans et al., 2006; Lapierre et al., 2013; Monteith et al., 2007; Roulet and Moore 2006; Tank et al., 2016). Evidence also suggests that the active layer depth in permafrost soil has increased, mobilizing previously frozen carbon stocks (Neff et al., 2006). In addition, warming and related vegetation changes have increased DOC flux from the Mackenzie River to the Arctic Ocean (Tank et al., 2016). However, permafrost thaw and increased groundwater contribution to Arctic rivers also have been linked to increased mineralization of organic carbon in the subsurface and changes in the proportion of DOC and DIC exports in Alaska's Yukon River basin (Striegl et al., 2005; Walvoord and Striegl 2007). Any decreases in organic carbon export, though, potentially may be offset by increased organic carbon runoff from vegetation change in low-lying regions (Dornblaser and Striegl 2015). The proportion of carbon mobilized under warming conditions that is mineralized to CO_2 versus exported as DOC remains unknown. Furthermore, research indicates that permafrost thaw also has increased CH_4 emissions since the 1950s as a result of degrading lake shorelines that contribute aged carbon (Walter Anthony et al., 2016). However, these emissions cannot be quantified at the national or continental scales.

Changes in aquatic carbon fluxes are linked directly to the residence time of water in both terrestrial and aquatic environments (Catalán et al., 2016). In particular, as precipitation increases, reducing water residence time, so do organic carbon fluxes from landscapes (Bianchi et al., 2013; Yoon and Raymond 2012). Knowing the contribution of groundwater versus surface water in streams is also important to understand CO_2 fluxes from terrestrial systems (Hotchkiss et al., 2015). The removal of organic carbon in lakes, streams, and rivers is positively related to its residence time (Catalán et al., 2016; Vachon et al., 2016). The half-life of organic carbon in inland waters is about 2.5 years, much shorter than the decades to millennia required for soil systems to completely turn over (Catalán et al., 2016). Some studies hypothesize that increases in precipitation caused by an altered climate will move carbon that would be stored in soils into aquatic environments where remineralization may accelerate the return of organic carbon to the atmosphere as CO_2 in high and temperate latitudes (Drake et al., 2015; Raymond et al., 2016). In addition, the installation or removal of dams will directly affect the quantity and form of carbon in aquatic environments by shifting water residence time, water surface areas, and sediment loads. Predicting how the overall carbon balance will shift across North America remains difficult because of complex interactions between inorganic and organic carbon within aquatic systems and the importance of anthropogenic change at the landscape scale (Butman et al., 2015; Lapierre et al., 2013; Regnier et al., 2013; Solomon et al., 2015; Tank et al., 2016).

14.5 Global, North American, and U.S. Context

14.5.1 A Global Carbon Cycle Perspective

Understanding the fluxes of carbon through inland waters in the context of the global carbon cycle remains an active area of research today. Of particular interest are 1) terrestrial carbon fluxes to inland waters; 2) carbon transformations within inland waters, especially movement into storage reservoirs and the atmosphere; and 3) carbon fluxes to coastal waters and large inland lakes. Using Equation 14.1, p. 571, assessment of components of the inland water carbon cycle can begin at the global, regional, and U.S. scales.

Globally, the component with the least uncertainty is the flux of carbon to coastal waters. Estimates of DOC flux to the coast, for instance, have remained around 0.2 ± 0.05 Pg C per year for the last 30 years, although these estimates often are based on the same underlying dataset (Dai et al., 2012; Meybeck 1982; Seitzinger et al., 2005). The DIC flux of 0.35 Pg C per year has been shown to result from strong linkages between lithology and climate, coupled with better global products for these drivers (Hartmann et al., 2014b). Global estimates of the POC flux to coastal waters have changed because of a large and evolving anthropogenic signal from POC trapping behind dams, with a total flux of 0.15 Pg C per year (Galy et al., 2015; Spitzy and Ittekkot 1991; Syvitski and Milliman 2007). The sum of DOC, DIC, and POC fluxes results in a C_{export} of 0.7 Pg C per year.

New global and ecosystem-specific estimates of CH_4 and CO_2 exchanges with the atmosphere have been facilitated by the growth of databases that capture measurements of these GHGs and by the ability to scale up estimates of inland water area and gas transfer velocity (Abril et al., 2014; Bastviken et al., 2011; Borges et al., 2015; Butman and Raymond 2011; Lauerwald et al., 2015; Raymond et al., 2013). New research suggests that Arctic and boreal lakes and ponds may release 16.5 Tg C per year (Wik et al., 2016), more than double previous estimates (Bastviken et al., 2011) for a similar range of latitudes. Evidence now shows that lake and river size, topography, land cover, and terrestrial productivity affect the total carbon dynamics in freshwaters (Butman et al., 2016; Holgerson and Raymond 2016; Hotchkiss et al., 2015; Stanley et al., 2016). However, these relationships are based on limited empirical data, and, although progress is being made, a mechanistic understanding that links landscapes to inland water carbon fluxes is still lacking (Hotchkiss et al., 2015). Furthermore, the fluxes of CH_4 and CO_2 per unit area of water surface are extremely high for very small streams and ponds (Holgerson and Raymond 2016), but these systems are not easily detected with remote sensing and have very few high temporal frequency studies (Feng et al., 2015; Koprivnjak et al., 2010).

Carbon dioxide flux from inland waters to the atmosphere ($C_{emissions}$) at the global scale is due to mostly large river systems and currently is estimated at 1.8 to 2.2 Pg C per year (Raymond et al., 2013). Recent data from the Amazon suggest that total global emissions could be as high as 2.9 Pg C per year (Sawakuchi et al., 2017). Carbon burial represents another large removal process for aquatic carbon. Global inland water burial estimates are fairly uncertain, ranging from 0.2 to 0.6 Pg C per year as C_{burial} (Battin et al., 2009b; Tranvik et al., 2009). Assuming that the carbon stock of inland waters is not changing with time and using compiled values only (Raymond et al., 2013) lead to the maximum possible terrestrial input being approximately 3.7 Pg C per year (Raymond et al., 2013), which represents the total carbon needed to balance the loss through coastal export, burial, and gas emissions. Internal primary production and respiration are known contributors to gas emissions, as well as burial. Therefore, verifying this 3.7 Pg C per year currently is not possible due to the diversity of terrestrial and inland water ecosystems, temporal variability of fluxes, and lack of studies of small end-member ecosystems.

14.5.2 Comparison Between Global and U.S. Carbon Fluxes

The fluxes of carbon from the United States (CONUS and Alaska) represent those with the highest confidence reported here and will be evaluated against those at the global scale. A comparison of global versus U.S. estimates of aquatic carbon fluxes shows similar patterns in the relative magnitude of carbon flux pathways. Applying the conservative global estimate for carbon burial of 0.2 Pg C per year (Tranvik et al., 2009), carbon emissions across the air-water interface are 60% of the total flux at the global scale and 63% at the U.S. scale (see Equation 14.1, p. 571, and Figure 14.2, p. 572). In contrast to estimates in SOCCR1, these results suggest that half of all aquatic carbon fluxes are releases of gases to the atmosphere. At the global and U.S. scales, lateral fluxes from land to coasts represent 24% and 26% of the total, respectively. It is important to note that globally, POC entrapment through burial, if assumed to be 0.2 Pg C per year, is nearly 6% of the total flux of carbon from inland waters. This amount increases to 16% if the burial term is considered to be 0.6 Pg C per year (Battin et al., 2009b). The range of estimates for the proportion of carbon entering sediments (i.e., 6% to 16%) globally bounds the more refined modeling for CONUS that suggests burial is 10% of the total.

Global and U.S. CO_2 emissions equal 17 and 13.6 g C per m^2 per year, respectively, indicating that CO_2 emissions from U.S. inland waters are 20% less than the global average per unit land area. Carbon burial per unit area varies from 1.5 to 4.5 g C per m^2 per year, very similar to the 1.9 g C per m^2 per year estimate obtained for CONUS and Alaska. Overall, per unit area, the total carbon flux at the global scale is 25% greater (at 24.8 g C per m^2 per year) than the 20.6 g C per m^2 per year estimated for the United States. The discrepancies between the U.S. and global areal fluxes increase if recently estimated values (Sawakuchi et al., 2017) are used for the comparisons (see Table 14.1, p. 576). These discrepancies may be due to differences in methodologies but also may reflect spatial variability in inland water ecosystem type. For example, the importance of tropical systems for carbon fluxes may drive the distribution of inland water fluxes at the global scale, even though tropical areas represent only a very small fraction of the ecosystems within CONUS.

14.5.3 Regional Differences of U.S. Carbon Fluxes

Carbon fluxes from inland waters differ across regions in CONUS, and the relative contributions of each flux component vary across space (Butman et al., 2016). In particular, lateral fluxes from the eastern portion of the Mississippi River basin are larger than gaseous emissions, while carbon burial dominates lake fluxes in the river's lower basin. Carbon dioxide emissions are dominant in systems that have steep topography and more acidic waters. Emissions of CO_2 are highest in the western regions of the Pacific Northwest, where both rainfall and topography drive large carbon inputs from primary production and topography enhances gas transfer (Butman et al., 2016). Inorganic carbon fluxes in the form of bicarbonate are large within watersheds with large areas of agriculture in the upper Midwest, an effect attributed to agricultural liming (Oh and Raymond 2006). Regional variability in inland water carbon fluxes is driven by the available inputs of carbon from variable land cover, as well as precipitation that facilitates the physical movement of that carbon from groundwater, soils, and wetlands.

14.5.4 North American Carbon Fluxes in Context

Total carbon fluxes from inland waters of North America were estimated using the results of the Regional Carbon Cycle Assessment and Processes (RECCAP) effort (see Table 14.1, p. 576) for emissions and lateral fluxes based on the scaling of empirical data (Hartmann et al., 2009; Mayorga et al., 2010; Raymond et al., 2013). The average burial rate of carbon based on land cover from CONUS and Alaska was used herein for calculations (Clow et al., 2015). The total carbon flux from inland waters is estimated to be 507 Tg C per year. About 48% of this carbon, or 247 Tg per year, consists of emissions across the air-water interface

from both lentic and lotic systems. The lateral flux of carbon to the coast is 105 Tg C per year, or 21% of the total. This estimate compares well with recent results derived from a spatially explicit coupled hydrological-biogeochemical model that suggest 96 (standard deviation 8.9) Tg C per year move laterally to coastal systems in North America (Tian et al., 2015). Finally, the burial of carbon within inland waters is estimated to be nearly 30% of the total flux, at 155 Tg C per year. These estimates are based on modeled export of carbon to coastal systems and broadly scaled estimates for CO_2 emissions derived from sparse datasets at high latitudes (Hartmann et al., 2014a; Raymond et al., 2013) and are considered uncertain.

14.6 Societal Drivers, Impacts, and Carbon Management

Human impacts on carbon movement and processing in inland waters include 1) land-use change that promotes the destabilization of soil carbon and increases erosion (Lal and Pimentel 2008; Quinton et al., 2010; Stallard 1998); 2) altered climate patterns that shift the timing and magnitude of precipitation and hydrological events (Clair and Ehrman 1996; Evans et al., 2007); 3) changes in nutrient and organic matter inputs that alter carbon processing and storage within aquatic environments (Humborg et al., 2004; Mayorga et al., 2010; Seitzinger et al., 2005); and 4) changes in temperature (Nelson and Palmer 2007). These effects are not independent of one another. However, inland waters are inherently difficult to evaluate in the context of carbon management, from either a sequestration or mitigation position. In contrast to forested ecosystems, the chemistry of inland waters changes rapidly on timescales from seconds to days in direct relation to the hydrological regime (Sobczak and Raymond 2015). Furthermore, the sources of carbon within inland waters are poorly characterized across spatial and temporal scales relevant to national-scale management decisions. A robust understanding of the impact that dams have on carbon transformation and fluxes to coastal systems would directly identify the connections between anthropogenic energy and water resource needs and the carbon cycling of inland waters (Deemer et al., 2016; Maeck et al., 2014; Teodoru et al., 2012). The research community is currently unable to identify whether all dammed systems cause increased carbon emissions, but recent synthesis efforts suggest that CO_2 and CH_4 emissions increase under conditions of high nutrients and with large inputs of terrestrial carbon (Barros et al., 2011; Deemer et al., 2016; Teodoru et al., 2012). Worldwide there are more than 1 million estimated dams (Lehner et al., 2011); of these, over 87,000 have heights >15 m (World Commission on Dams 2000). Research is needed to evaluate the impact that this level of damming has on the aquatic carbon cycle.

14.7 Synthesis, Knowledge Gaps, and Outlook

14.7.1 Summary

Advances in the ability to manipulate large databases of carbon chemistry covering the United States, coupled with new methods for spatial analysis, have enabled new and robust estimates for carbon fluxes from inland waters in CONUS and Alaska. By identifying and including CO_2 emissions, the U.S. fluxes of carbon are estimated to be approximately 193 Tg C per year. These fluxes are dominated by river and stream networks exporting up to 59.8 Tg C per year to the coast and emitting nearly 85.9 Tg C per year as CO_2 to the atmosphere. Availability of data is limited from Mexican inland waters. Deep, tropical, warm monomictic lakes constitute carbon sinks primarily as POC, while shallow, tropical—and mostly eutrophic—lakes are sources of CO_2 and CH_4 to the atmosphere. Further data collection is needed to properly assess carbon cycling within inland waters at the national scale in both Canada and Mexico. However, based on estimates presented here, the carbon flux from inland waters is now understood to be four times larger than estimates presented in SOCCR1.

14.7.2 Key Knowledge Gaps and Current Opportunities

Peer-reviewed and detailed estimates are not currently available for carbon fluxes from inland waters

within Mexico and Canada. Further collaboration is necessary among monitoring efforts in these countries and the United States to properly develop a spatially explicit inland water database on carbon concentration and carbon fluxes across North America. In addition, robust estimates of annual carbon fluxes for the Laurentian Great Lakes are not yet possible, a surprising limitation given their importance as the largest inland waters on Earth. Preliminary data suggest that these systems vary from a net carbon source to the atmosphere in Lake Superior, Lake Michigan, and Lake Huron to a net carbon sink in Lake Erie and Lake Ontario. By combining a box model analysis with a literature review of respiration, river inputs, and burial, McKinley et al. (2011) conclude that the Great Lakes efflux lies between 2.3 and 36 Tg C per year. If future research suggests emissions near 2.3 Tg C per year, then the emission of carbon as CO_2 may be nearly balanced by carbon burial (Einsele et al., 2001). However, if new data suggest significantly higher emissions, such results would increase the importance of the Great Lakes with respect to total carbon fluxes from the United States and Canada. The Great Lakes are heavily affected by anthropogenic disturbance through nutrient enrichment and invasive species, with unknown impacts on carbon cycling.

Also unavailable is a comprehensive estimate for the contribution of CH_4 to carbon emissions for inland waters of North America. Data on CH_4 do not yet exist across space and time to properly scale to national and continental levels, though significant progress is being made (Holgerson and Raymond 2016; Stanley et al., 2016; Wik et al., 2016).

One major methodological advancement in past years is *in situ* probe systems (Baehr and DeGrandpre, 2004). Probes to measure aspects of the carbon cycle are becoming more accurate and affordable (Bastviken et al., 2015; Johnson et al., 2010), and the research community is advancing methodologies to process high-temporal datasets (Downing et al., 2012), identifying the role that storm events may play in carbon fluxes. The possibility now exists to instrument inland water systems along the aquatic continuum from when water emerges from the terrestrial interface to when it is exported to the coast or large inland lakes. Such instrumentation will facilitate understanding of the transformations of terrestrial carbon during transport to inland waters and the controls on this transport. However, deploying sensor systems alone is not enough to ensure the development of the data needed to reduce uncertainties. The inland water carbon cycle science community must learn from the efforts of organizations like the International Ocean Carbon Coordination Project to develop standard approaches and reference materials for study comparison and reproducibility. Furthermore, future research needs to take advantage of developments in both large- and small-scale data acquisition and should attempt nested watershed studies across scales to understand the carbon cycling within inland water environments. These studies, coupled with new methods to quantify surface waters at the global scale, particularly small streams and ponds, will help further constrain the importance of inland waters to the Earth biogeochemical system under a changing climate (Pekel et al., 2016).

At 193 Tg C per year, the fluxes of carbon through inland waters of the United States are significant. The scaled value of 507 Tg C per year for North America represents an estimate that requires further science to reduce uncertainties. In the context of the overall cycling of carbon among terrestrial, wetland, and aquatic environments, there are important methodological differences that must be considered when using the estimates of carbon flux from inland waters. The aquatic carbon fluxes presented herein are derived from the modeling of fluxes to the coast, lake sediments, and the atmosphere. The quantification of the lateral flux of carbon to estuarine systems is perhaps the most well constrained, as it is derived from long-term monitoring of water flow and decades of direct measurements of carbon concentration. The emission of CO_2 from water surfaces is more uncertain. The difficulty of quantifying this emission is compounded by the ephemeral nature of small streams, along with a lack of detailed spatial information

on their total length and surface area. As suggested in this chapter, small streams and ponds represent a large fraction of the CO_2 emissions from inland waters to the atmosphere, important when scaling fluxes across the United States and the world. Furthermore, apportioning the carbon in an aquatic environment to its source (e.g., autochthonous versus allochthonous) currently is not possible. This gap in understanding removes an ability to differentiate, for example, soil respiration that simply has changed location into an aquatic ecosystem from in-stream respiration.

The importance of erosional fluxes of carbon to North American inland waters also cannot be properly assessed. The lateral transport of soil carbon and the concurrent fluxes of CO_2 returning to the atmosphere in China suggest that upwards of 45 Tg C per year enter inland waters, thus representing a terrestrial carbon sink (Yue et al., 2016). However, this type of calculation does not fully account for replacement of carbon within soils, the remineralization of organic carbon during transport, direct inputs of inorganic carbon, or the lateral fluxes of dissolved carbon to the coast. Therefore, caution is warranted when including inland waters in a mass balance for total carbon accounting. To fully understand the role that inland waters play across the land-water continuum, studies must be conducted at the watershed scale, coupling terrestrial and inland water processes. These measurements will help constrain future modeling studies that require coupling between hydrology and biogeochemistry.

SUPPORTING EVIDENCE

KEY FINDING 1

The total flux of carbon—which includes gaseous emissions, lateral flux, and burial—from inland waters across the conterminous United States (CONUS) and Alaska is 193 teragrams of carbon (Tg C) per year. The dominant pathway for carbon movement out of inland waters is the emission of carbon dioxide gas across water surfaces of streams, rivers, and lakes (110.1 Tg C per year), a flux not identified in the *First State of the Carbon Cycle Report* (SOCCR1; CCSP 2007). Second to gaseous emissions are the lateral fluxes of carbon through rivers to coastal environments (59.8 Tg C per year). Total carbon burial in lakes and reservoirs represents the smallest flux for CONUS and Alaska (22.5 Tg C per year) (*medium confidence*).

Description of evidence base

Estimates for the export of carbon to U.S. coasts have been well documented through long-term observations (Stets and Striegl 2012) and syntheses (Butman et al., 2016; Stackpoole et al., 2016; Zhu and McGuire 2016). Carbon burial is derived from recent model results (Clow et al., 2015). Gaseous emissions of CO_2 were originally assessed in Butman and Raymond (2011) for streams and rivers and McDonald et al. (2013) for lakes and reservoirs of CONUS only. Previous data do exist to support inland waters as dominated by supersaturated conditions (Striegl et al., 2012; Tranvik et al., 2009).

The finding that the dominant pathway for carbon loss through inland waters is through surface emissions was identified in Richey et al. (2002) and Cole et al. (2007) and quantified for CONUS in (Butman and Raymond 2011). Estimates that support this finding for Alaska are presented in Zhu and McGuire (2016). McDonald et al. (2012) showed that across CONUS, lake carbon burial and lake emissions are similar in magnitude when considered at the national scale, with regional variation based on the input of dissolved inorganic carbon (DIC) to lake systems.

Major uncertainties

Large uncertainties exist for the emission of CO_2 from stream and river systems based on empirical estimates of the gas transfer velocity of CO_2 presented in Raymond et al. (2012). The modeling of gas transfer is poorly constrained under high-flow conditions in steep topography. High levels of uncertainty also exist regarding the temporal dynamics of both lentic and lotic CO_2 emissions (Battin et al., 2008; Striegl et al., 2012; Tranvik et al., 2009), where limited data exist to assess carbon gas concentrations under ice or storm flow conditions.

Uncertainties also exist regarding the use of the empirical model for carbon burial presented in Clow et al. (2015). Limited concentration data exist for lakes in Alaska, and there may be significant bias in the concentrations used to scale lake fluxes across regions (Stackpoole et al., 2017a; Zhu and McGuire 2016). These constraints may result in overestimates of emissions. In addition, limited data on carbon burial exist for northern latitudes, resulting in the use of empirical models derived from samples that do not capture the level of variability that exists across Alaska (Stackpoole et al., 2016).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

The overall confidence level of medium reflects 1) advancements in inland water spatial representations in a global information system (GIS) format to develop surface areas, 2) completion

of datasets enabling the calculation of lateral fluxes, and 3) advancements in databases relevant to sedimentation rates in U.S. lakes and reservoirs. Confidence is reduced because modeling approaches available to estimate gas transfer velocities used for calculating carbon emissions are limited, and there are few chemical measurements in small stream systems.

Summary sentence or paragraph that integrates the above information

For Key Finding 1, individual flux terms (i.e., lateral flux, CO_2 emission, and carbon burial) each have a medium to high level of certainty. This reflects the high confidence in the spatial representation of the chemical data for CONUS and Alaska, as well as the length of monitoring for water chemistry within CONUS and Alaska.

KEY FINDING 2

Based on estimates presented herein, the carbon flux from inland waters is now understood to be four times larger than estimates presented in SOCCR1. The total flux of carbon from inland waters across North America is estimated to be 507 Tg C per year based on a modeling approach that integrates high-resolution U.S. data and continental-scale estimates of water area, discharge, and carbon emissions. This estimate represents a weighted average of 24 grams of carbon per m^2 per year of continental area exported and removed through inland waters in North America (*low confidence*).

Description of evidence base

Initial data presented in SOCCR1 did not acknowledge emission of carbon across the air-water interface. The estimate of 507 Tg C per year is based on well-constrained estimates of water discharge presented in Mayorga et al. (2010), Seitzinger et al. (2005), and compared with Dai et al. (2009, 2012). Estimates for the export of carbon modeled with water discharge are provided through the Regional Carbon Cycle Assessment and Processes (RECCAP) effort of the Global Carbon Project. Gaseous emissions of CO_2 are presented in Raymond et al. (2013) based on similar methods presented in Butman and Raymond (2011). Areal rates of carbon flux through inland waters for CONUS and Alaska match those for North America.

Major uncertainties

Estimates and uncertainties to scale the emissions of CO_2 from streams, rivers, and lake systems from CONUS to North America have already been provided. However, the application of CONUS lake carbon burial rates derived from Clow et al. (2015) to the total lake areas from Aufdenkampe et al. (2011) is unique. The methods used an average burial rate of about 110 g C per m^2 per year, which is lower than those used in recent global estimates for lake and reservoir burial (Battin et al., 2009a). This burial rate is not dynamic and does not fully capture the spatial heterogeneity found across North America (Clow et al., 2015).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Overall level of confidence is lower for the region of North America due to the different modeling approach, lack of data that exist in both Canada and Mexico, and the simplified application of U.S. data to a region that covers many different ecosystem types.

Summary sentence or paragraph that integrates the above information

For Key Finding 2, confidence is low for estimates of inland aquatic carbon fluxes for North America because of a general lack of data available from Mexico and Canada, including CO_2 emissions or burial estimates. Methods developed for datasets within CONUS were applied to these two regions.

KEY FINDING 3

Future research can address critical knowledge gaps and uncertainties related to inland water carbon fluxes. This chapter, for example, does not include methane emissions, which cannot be calculated as precisely as other carbon fluxes because of significant data gaps. Key to reducing uncertainties in estimated carbon fluxes is increased temporal resolution of carbon concentration and discharge sampling to provide better representations of storms and other extreme events for estimates of total inland water carbon fluxes. Improved spatial resolution of sampling also could potentially highlight anthropogenic influences on the quantity and quality of carbon fluxes in inland waters and provide information for land-use planning and management of water resources. Finally, uncertainties could likely be reduced if the community of scientists working in inland waters establishes and adopts standard measurement techniques and protocols similar to those maintained through collaborative efforts of the International Ocean Carbon Coordination Project and relevant governmental agencies from participating nations.

Description of evidence base

Methane CH_4 emissions can be a significant source of carbon to the atmosphere from Arctic lakes (Wik et al., 2016). Fixed-interval sampling protocols may miss large storm events and may critically bias estimates for total carbon fluxes to the coast (Raymond et al., 2012). Management of water resources in reservoir systems may influence the magnitude of carbon burial and emissions, driving systems to be more or less effective at storing or releasing carbon over time (Deemer et al., 2016).

Major uncertainties

Uncertainties are presented within the evidence base. Major uncertainties include 1) the relative importance of storm events or perturbations in the hydrological cycle to carbon export to coastal systems, 2) the magnitude of CH_4 fluxes over time and across seasonal and latitudinal gradients, 3) the role that management of water resources plays in the movement and storage of carbon over time, and 4) the lack of established protocols for comparable sampling and scaling of carbon emissions across inland waters.

Summary sentence or paragraph that integrates the above information

For Key Finding 3, overall spatial and temporal data are not adequate to estimate the magnitude of CH_4 fluxes from inland waters or to capture the influence of storm events or management on inland water carbon fluxes.

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15 Tidal Wetlands and Estuaries

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KEY FINDINGS

1. The top 1 m of tidal wetland soils and estuarine sediments of North America contains 1,886 ± 1,046 teragrams of carbon (Tg C) (*high confidence, very likely*).
2. Soil carbon accumulation rate (i.e., sediment burial) in North American tidal wetlands is currently 9 ± 5 Tg C per year (*high confidence, likely*), and estuarine carbon burial is 5 ± 3 Tg C per year (*low confidence, likely*).
3. The lateral flux of carbon from tidal wetlands to estuaries is 16 ± 10 Tg C per year for North America (*low confidence, likely*).
4. In North America, tidal wetlands remove 27 ± 13 Tg C per year from the atmosphere, estuaries outgas 10 ± 10 Tg C per year to the atmosphere, and the net uptake by the combined wetland-estuary system is 17 ± 16 Tg C per year (*low confidence, likely*).
5. Research and modeling needs are greatest for understanding responses to accelerated sea level rise; mapping tidal wetland and estuarine extent; and quantifying carbon dioxide and methane exchange with the atmosphere, especially in large, undersampled, and rapidly changing regions (*high confidence, likely*).

Note: Confidence levels are provided as appropriate for quantitative, but not qualitative, Key Findings and statements.

15.1 Introduction

Estuaries and tidal wetlands are dynamic ecosystems that host high biological production and diversity (Bianchi 2006). They receive large amounts of dissolved and particulate carbon and nutrients from rivers and uplands and exchange materials and energy with the ocean. Estuaries and tidal wetlands are often called biogeochemical "reactors" where terrestrial materials are transformed through interactions with the land, ocean, and atmosphere. Work conducted in the past decade has clearly shown that open-water estuaries as a whole can be strong sources of carbon to the atmosphere—both carbon dioxide (CO_2) and methane (CH_4)—despite the fact that how degassing (i.e., gas emissions) rates vary in space and time in many estuaries is unknown (Borges and Abril 2011; Cai 2011). In contrast, tidal wetlands represent a small fraction of the land surface but are among the strongest long-term carbon sinks, per unit area, because of continuous organic carbon accumulation in sediments with rising sea level (Chmura et al., 2003). Estuaries are included here in the *Second State of the Carbon Cycle Report* (SOCCR2) but were not included in the *First State of the Carbon Cycle Report's* (SOCCR1; CCSP 2007) assessment of coastal carbon cycling. Estuaries have been reviewed in recent synthesis activities, particularly the Coastal CARbon Synthesis (CCARS; Benway et al., 2016). Tidal wetlands were included in the wetlands chapter of SOCCR1 but are separated from inland wetlands in this SOCCR2 assessment to reflect their unique connections to estuarine and ocean dynamics. Consistently missing from previous fieldwork and syntheses are important annual carbon exchanges (including CO_2 and CH_4 flux) across boundaries of intertidal (hereafter, wetland) and subtidal ecosystems and deeper waters (hereafter, estuarine). As subsystems of an integrated coastal mixing zone, this lack of information limits understanding of the relative roles of wetlands and estuaries in carbon cycling at the critical land-ocean margin. An updated synthesis of current knowledge and gaps in quantifying the magnitude and direction of carbon fluxes in dynamic estuarine environments is presented herein.

According to Perillo and Picollo (1995) and Pritchard (1967), estuaries are commonly defined as "semi-enclosed coastal bodies of water that extend

to the effective limit of tidal influence, within which seawater entering from one or more free connections with the open sea, or any saline coastal body of water, is significantly diluted with fresh water [sic] derived from land drainage, and can sustain euryhaline biological species from either part or the whole of the life cycle." For the purpose of this report, the landward boundary of estuarine zones is defined as the "head of tide" (i.e., the maximal boundary of tidal expression in surface water elevation) and the shoreward limit of the continental shelf (i.e., the relatively shallow sea that extends to the edge of continental crust). While island coastlines are included in the overall SOCCR2 domain (namely Hawai'i, Puerto Rico, and the Pacific Islands), due to reliance on recent synthesis products for carbon accounting, the focus herein is exclusively on continental coastlines where stocks and fluxes have been quantified and mapped most comprehensively. Section 15.2, this page, provides a brief historical overview of carbon flux in estuaries and tidal wetlands with an emphasis on coastal processes with global applicability. Section 15.3, p. 601, compiles information on carbon fluxes of estuaries and tidal wetlands of North America in the global context and from regional perspectives. Through literature summaries and data syntheses, Section 15.4, p. 609, provides new estimates of selected fluxes and stocks in tidal wetlands and estuaries of North America. Section 15.5, p. 615, discusses new and relevant coastal carbon observations through indicators, trends, and feedbacks, and Section 15.6, p. 619, reports on management and decisions associated with societal drivers and impacts within the carbon cycle context. Finally, Section 15.7, p. 620, provides a synthesis that summarizes conclusions, gaps in knowledge, and near-future outlooks.

15.2 Historical Context, Overview of Carbon Fluxes and Stocks in Tidal Wetlands and Estuaries

Tidal wetlands and estuaries of North America vary in relative area depending on coastal topography, historic rates of sea level rise, and inputs of suspended solids from land. In drowned river valleys (e.g., Chesapeake Bay) and fjords (e.g., Puget Sound) that are topographically steep, estuarine habitat is the dominant subsystem (Dalrymple et al., 1992). In contrast, the ratio of tidal wetland area to estuarine area is relatively high (Day et al., 2013), though still less than one (Najjar et al., 2018) along coastal plains.

The land-sea interface that defines the presence of tidal wetlands and estuaries (i.e., river-sea mixing zones) is itself extremely dynamic over broad spatial and temporal scales. The current configuration of tidal wetlands and estuaries is the result of processes that have been occurring since the last glacial maximum, roughly 18,000 years ago. Over the past 6,000 years, when rates of sea level rise slowed to less than 1 mm per year, tidal wetlands increased in size relative to open-water estuaries, as bay bottoms filled with sediments from uplands and tidal wetlands prograded into shallow open-water regions and transgressed across uplands (see Figure 15.1, p. 599; Redfield 1967). Concomitant with increasing sea levels, tidal wetlands maintained their relative elevation as wetland plants trapped suspended sediments from tidal floodwaters, as well as accumulated organic matter in soils. Factors that affect tidal wetland area and relative elevation, through lateral and vertical erosion and accretion, include 1) rate of sea level rise, 2) land subsidence or isostasy (glacial rebound), 3) delivery and deposition of suspended sediment, 4) balance between wetland gross primary production (GPP) and respiration of all autotrophs and heterotrophs (R_{AH}), 5) sediment compaction, and 6) slope of land at the land-water interface (Cahoon 2006).

Tidal wetlands are among the most productive ecosystems on Earth, continuously accumulating organic carbon that results from environmental conditions that inhibit organic matter decomposition. As a result, intact tidal wetlands are capable of storing vast amounts of *autochthonous* organic carbon (i.e., fixed through photosynthesis on site) as well as intercepting and storing *allochthonous* organic carbon (i.e., produced off site, terrigenous; Canuel et al., 2012). Documented carbon-related

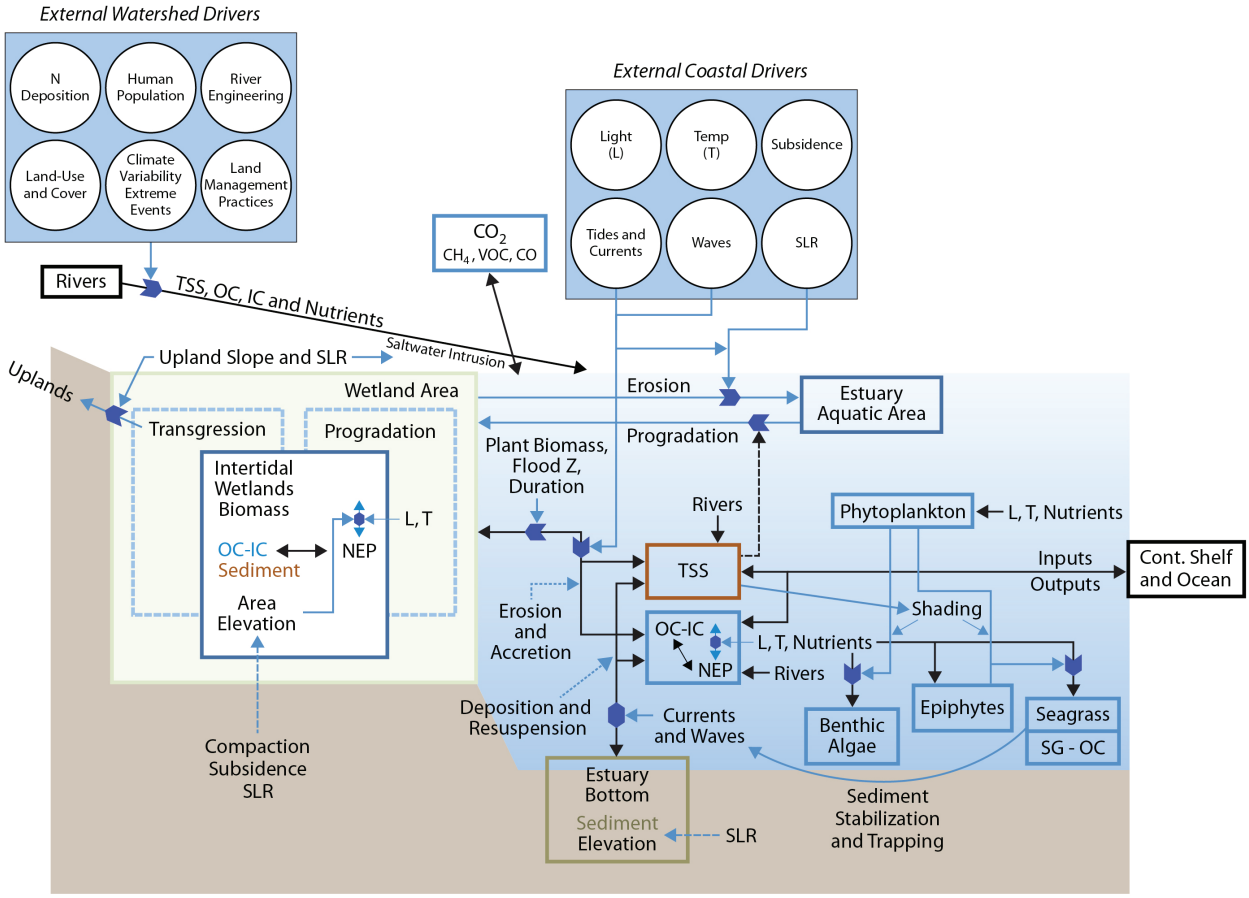

Figure 15.1. Conceptual Model of Coastal Tidal Wetlands and Estuaries and Their Linkages with Adjacent Terrestrial and Oceanic Systems. The drivers, processes, and factors depicted here largely control carbon dynamics in these systems. Net ecosystem production (NEP) is equal to gross primary production minus the sum of heterotrophic and autotropic respiration. [Key: N, nitrogen; CO_2, carbon dioxide; CH_4, methane; VOC, volatile organic compound; CO, carbon monoxide; L, light; T, temperature; TSS, total suspended solids; OC, organic carbon; IC, inorganic carbon; Z, elevation; SG, seagrass; SLR, sea level rise]

ecosystem benefits, referred to as "services," include significant uptake and storage of carbon in wetland soils, as well as export to the ocean of organic matter, which increases the productivity of coastal fisheries (Day et al., 2013). Globally, tidal wetlands are strongly variable in age and structure. Some of today's tidal wetlands have persisted for more than 6,500 years, accumulating to a depth of up to 13 m of tidal peat (Drexler et al., 2009; McKee et al., 2007; Peteet et al., 2006), but some wetlands are young and shallow because of recent human influences that enhanced sediment delivery to nearshore waters. Examples include the colonial-era East Coast (Kirwan et al., 2011) and gold rush in California (Palaima 2012). Because human development is preferentially concentrated on coastlines, tidal wetlands have been subject to active loss through development pressures. While tidal wetland losses have slowed in the United States, global tidal wetland losses are currently estimated at 0.5% to 3% annually (Pendleton et al., 2012), with estimates depending on the ecosystem, time frame, and methods used in evaluation (Hamilton and Casey 2016; Spalding et al., 2010). Loss of carbon stocks through wetland drainage and erosion remains poorly modeled due to limited mapping and quantification of

initial carbon stock conditions (Chmura 2013). Further, more subtle rates of wetland loss, through drowning or erosion, may be underestimated by remote-sensing techniques insensitive to small-scale changes observed through aerial photography (e.g., Schepers et al., 2017; Watson et al., 2017).

Estuarine waters are a small but productive fraction of coastal waters (Cloern et al., 2014; Wollast 1991). The role of coastal zones as sinks or sources of atmospheric CO_2 is still poorly understood (Borges 2005; Borges et al., 2005; Smith and Hollibaugh 1997), resulting in a lack of consensus toward their role in global carbon budgets (Cai 2011; Wollast 1991; Borges and Abril 2011; Chen et al., 2013). With poorly characterized boundary conditions, estuarine waters have strong upland and ocean-based drivers, leading to strong seasonality in carbon transport and transformation. Geological records suggest that estuarine carbon storage was enhanced in the past 6,000 years and during recent centuries by watershed activities (Colman et al., 2002), but responses were varied. Human activities initially increased the delivery of organic materials to estuaries (e.g., forest clearing) and thus drove them to support higher net respiration (and likely greater sources of atmospheric CO_2); however, more recent human activities (e.g., dam construction and fertilizer use) have greatly reduced sediment and organic matter delivery but increased nutrient fluxes to many estuaries (Bianchi and Allison 2009; Galloway et al., 2008), driving estuarine waters to be less heterotrophic and, possibly, causing more net carbon burial and export to the ocean (Regnier et al., 2013). While North American estuarine conditions vary along coasts according to upstream land use, the most significant human-induced change to estuarine carbon dynamics over the past century is certainly increased nutrient loading (Schlesinger 2009), which has led to eutrophication and hypoxia in estuaries and continental shelves. Eutrophication promotes carbon uptake and pH increase in surface estuarine waters (Borges and Gypens 2010), but it also may enhance acidification when organic matter fixed by photosynthesis is respired. In stratified estuarine waters, respiration-induced CO_2 and poor buffering capacity could greatly reduce pH and carbonate saturation states to levels much lower than those resulting from the increase of anthropogenic CO_2 in the atmosphere and its subsequent uptake in surface waters (Cai 2011, Cai et al., 2017; Feely et al., 2010). The particularly large pH changes and the difficulty in predicting acidification in estuaries have motivated many scientists to study estuarine acidification in addition to ocean acidification (Duarte et al., 2013).

Estuaries generally have more interannual variability in carbon dynamics than do tidal wetlands, a phenomenon reflecting the balance of exchanges with terrestrial watersheds, tidal wetlands, and the continental shelf (Bauer et al., 2013). Processing of material inputs from land and tidal wetlands determines the autotrophic-heterotrophic balance of the estuary; this processing reflects the biological, chemical, and physical structure of the receiving estuary, as well as the nature of the inputs themselves. The autotrophic-heterotrophic balance of an estuary is especially sensitive to the water residence time (largely a function of freshwater runoff, tidal mixing, and estuarine geometry), the ratio of inputs of organic carbon (primarily from land and tidal wetlands) to inorganic nutrients (primarily from land), the degradability of the organic carbon input (Hopkinson and Vallino 1995; Kemp et al., 1997; Herrmann et al., 2015). The relative abundance of pelagic (i.e., phytoplankton-dominated) versus benthic (i.e., seagrass- or benthic algal–dominated) communities is also a major factor affecting estuarine carbon dynamics. The availability of light is perhaps the major constraint on the distribution of benthic autotrophic communities. Light availability to the benthos depends on estuarine depth and water clarity, which in turn are related to concentrations of suspended solids and phytoplankton in the estuarine water column. In nitrogen-enriched estuarine waters, high-phytoplankton biomass and epiphytic algae decrease light availability to benthic autotrophic communities, sometimes resulting in a complete loss of seagrass habitats (Howarth et al., 2000). In shallow systems, benthic macroalgae often dominate system dynamics. Seagrass, because of its ability to control

wave and current strength, can play a major role in limiting sediment resuspension, thereby maintaining high water clarity (van der Heide et al., 2011). Estuaries typically are heterotrophic and release CO_2 to the atmosphere, largely as a result of their processing of organic carbon inputs from watersheds (Raymond and Bauer 2001) and adjacent tidal wetlands (Bauer et al., 2013; Cai and Wang 1998; Wang and Cai 2004). For example, U.S. Atlantic coastal estuaries as a whole are net heterotrophic (Herrmann et al., 2015); all but three of 42 sites in the U.S. National Estuarine Research Reserve System were net heterotrophic over a year (Caffrey 2004), and a global survey concluded that 66 out of 79 estuaries were net heterotrophic (Borges and Abril 2011). At the same time, estuaries can serve as significant long-term organic carbon sinks through sedimentation of terrestrial inputs and seagrass organic matter burial (Duarte et al., 2005; Hopkinson et al., 2012; McLeod et al., 2011; Nellemann et al., 2009).

15.3 Global, North American, and Regional Context

Similar to the approach used by Benway et al. (2016), this assessment divided the North American coastline into four main subregions (see Figure 15.2, p. 602): the Atlantic Coast (Nova Scotia, Canada, to the southern tip of Florida, United States), the Gulf of Mexico, the Pacific Coast (southernmost Mexico to the Seward Peninsula, United States), and the High-Latitude Coast (the boreal and Arctic coastlines of Alaska and Canada between the Seward Peninsula and Nova Scotia). There are notable differences in carbon cycling among these four major subregions of North America. This section presents a descriptive analysis of those processes by subregion.

15.3.1 Atlantic Coast Estuaries and Tidal Wetlands

Estuaries of the North American Atlantic coast are the most extensive and diverse in structure and function within North America. Relatively shallow and driven primarily by landward influences, they are strongly influenced by freshwater flow and quality from rivers and groundwater. From boreal to subtropical latitudes, a wide range of biotic activity (e.g., photosynthesis and respiration) is seen from Nova Scotia to Florida.

Atlantic Coast Estuaries

South Atlantic Bight. The South Atlantic Bight (SAB: southern tip of Florida to Cape Hatteras, North Carolina) is a passive, western boundary current margin with broad shelf areas, extensive shoals, and a series of barrier islands, behind which are lagoons. Freshwater delivery in the SAB is through rivers that are nearly evenly located along the coast. These rivers carry high loads of dissolved organic carbon (DOC). Because of short transit times through the estuaries, much of the DOC is discharged onto the shelf, supporting respiration, net heterotrophy (Hopkinson 1985, 1988), and CO_2 degassing on the inner-shelf regions (Jiang et al., 2013). Much is known about the export of organic matter from SAB watersheds. The SAB salt marshes are tremendous sinks of CO_2 and organic carbon from uplands, whereas the estuarine waters are strong sources of CO_2 to the atmosphere—sources that are largely supported by organic matter and dissolved inorganic matter (DIC) export from both wetland saltmarshes and from SAB watersheds (Wang and Cai 2004; Cai 2011; Herrmann et al., 2015; Hopkinson 1988).

Mid-Atlantic Bight and Gulf of Maine. The Mid-Atlantic Bight (MAB: Cape Hatteras, North Carolina, to Cape Cod, Massachusetts) and Gulf of Maine (GOM: Cape Cod to Nova Scotia) are characterized by large estuaries. Inorganic carbon from carbonate weathering and organic matter remineralization accounts for the majority of riverine carbon input to the MAB (Hossler and Bauer 2013; Moosdorf et al., 2011). Generally, aqueous organic matter concentrations are higher in southern MAB rivers and can be more than half the riverine carbon load to estuaries (Stets and Striegl 2012; Tian et al., 2015). Lateral exchange with wetlands is an important carbon input to MAB waters and has been linked to net heterotrophy and air-water CO_2 efflux in narrow, marsh-dominated subestuaries (Baumann et al., 2015; Raymond et al., 2000; Wang

Figure 15.2. Map of the Main Coastal Regions and Associated Drainage Basins of North America. In this chapter, the North American coastline is broken up into four main regions: Atlantic Coast, Gulf of Mexico, Pacific Coast (including the Sea of Cortez, Gulf of Alaska, and Bering Sea), and High Latitudes (including the Chukchi Sea, Beaufort Sea, Hudson Bay, Labrador Sea, and Gulf of Saint Lawrence). [Figure source: Redrawn from U.S. Department of Interior]

et al., 2016). However, larger MAB estuaries can be seasonal or annual sinks for atmospheric CO_2 because of stratification and high rates of internal production (Crosswell et al., 2014; Joesoef et al., 2015). Supporting this result, recent carbon budget studies have estimated that MAB estuaries are near metabolic balance and that total organic carbon (TOC) export to the coastal ocean is about equal to riverine TOC input (Herrmann et al., 2015; Crosswell et al., 2017). The GOM shares many of these traits, but its TOC input is low due to its small catchment area (Najjar et al., 2018).

Atlantic Coast Tidal Wetlands

Despite some similarity in vegetation community composition (e.g., estuarine emergent *Spartina* spp., dominant in saline habitats), Atlantic coast tidal marshes are extensive and topographically varied in structure, from the more patchy, organic-rich GOM and MAB soils to the extensive, mineral-rich plains of the SAB. Biomass stocks of the dominant plant species, *Spartina alterniflora,* show a decrease with latitude (Kirwan et al., 2009), with the notably productive SAB marshes (Gallagher et al., 1980; Schubauer and Hopkinson 1984) exporting large amounts of marsh grass–derived organic matter and CO_2 into the estuaries and nearshore ocean where respiration and degassing occur (Jiang et al., 2008; Wang and Cai 2004). Soil carbon burial is not commensurate with productivity, as increased organic matter decomposition (Kirwan and Blum 2011) may negate any latitudinal productivity gradients. More important than latitudinal patterns for carbon flux accounting are within-watershed patterns of marsh elevation (i.e., low marsh versus high marsh), tidal range (e.g., microtidal eastern Florida versus extreme macrotidal Bay of Fundy), and salinity regimes. Freshwater tidal wetlands (both marsh and forest) make up 21% of tidal wetlands of the eastern United States (Hinson et al., 2017). Localized hotspots for soil carbon stock change also occur along the East Coast because of physical drivers such as sea level rise (Sallenger et al., 2012) and storm-induced erosion (Cahoon 2006). Estimated net ecosystem exchange (NEE) of atmospheric CO_2 from chamber and eddy covariance systems illustrates that vertical fluxes dominate carbon inputs to many East Coast tidal wetlands (Forbrich and Giblin 2015; Kathilankal et al., 2008). Much of this NEE is exported to ocean subsystems in particulate and dissolved forms, with lateral exports of DIC and DOC fluxes representing as much as 80% of annual carbon inputs (Wang and Cai 2004; Wang et al., 2016). Further, the role of groundwater flows in driving carbon fluxes, as well as nutrient fluxes that alter estuarine processes, is varied and poorly understood (Kroeger and Charette 2008; Moore 1996).

15.3.2 Gulf of Mexico Estuaries and Tidal Wetlands

Variability of Gulf of Mexico (GMx) estuaries is due, in part, to the variable forcing at their boundaries, including groundwater (dominating the Mexican coastline), rivers (dominating the U.S. coastline), wind, bathymetry, and ocean currents (e.g., the Loop Current). Gulf of Mexico tidal wetlands share many species but notably are experiencing enhanced mangrove encroachment and land subsidence.

Gulf of Mexico Estuaries

Estuarine GMx environments are microtidal with winds and river flows exerting strong control on water levels. On the extensive subtidal carbonate benthos, extensive seagrass meadows (e.g., *Thalassia*) persist and are known to recover rapidly from disturbance (e.g., Thorhaug et al., 2017). There is a paucity of data on air-water CO_2 flux in GMx estuaries. However, the lower-river portion of the two largest rivers, the Mississippi and the Atchafalaya, are strong sources of CO_2 to the atmosphere because the partial pressure of CO_2 (pCO_2) ranges from about 1,000 microatmospheres (µatm: a unit of pressure defined as 101,325 Pascals or 1.01325 bar) in winter to about 2,200 µatm in summer, but some large bays (e.g., Terrebonne Bay) have substantially lower pCO_2 (Huang et al., 2015). In comparison, despite relatively low pCO_2 (about 500 µatm), a semi-arid lagoonal estuary in northwestern GMx has a CO_2 efflux of 149 ± 40 grams of carbon (g C) per m^2 per year due to windy conditions all year

long (Yao and Hu 2017), an amount comparable to other lagoonal estuaries in the world (Laruelle et al., 2014). A strong climatic gradient from northeast to southwest along the northwestern GMx coast leads to riverine freshwater export decreasing by a factor of two (Montagna et al., 2009), with large interannual variability. This hydrological variability exerts strong control on estuarine CO_2 fluxes in this region.

Gulf of Mexico Tidal Wetlands

As of 2017, 52% of conterminous U.S. tidal wetlands are located within GMx, with Louisiana alone containing 40% of all the saltwater wetlands in the United States (Dahl 2011; Edwards and Proffitt 2003). While the GMx U.S. coastline is dominated by emergent marsh vegetation and the Mexican coastline is dominated by mangrove vegetation (see Table 15.1, this page), a wide range of salinity and geomorphic conditions promote structural diversity throughout GMx from tidal freshwater forests to floating peatlands to brackish and saline marshes. For the past two decades, other coastlines have been relatively stable in their tidal wetland extent but GMx is experiencing rapid transitions. Though there is active delta building at the Atchafalaya River outflow, tidal wetland conversion to open water (i.e., wetland loss) is common in GMx as a result of land subsidence, coastal storms, sea level rise, nutrient enrichment, and a lack of sediment delivery to compensate for ongoing compaction. The fate of wetland soil carbon following erosion or conversion to open water is poorly understood but important for conducting carbon accounting, particularly in GMx (DeLaune and White 2011; Lane et al., 2016). Climate shifts are also accelerating changes in wetland cover (Gabler et al., 2017), including mangrove encroachment on salt marshes in Texas, Louisiana, and Florida (Krauss et al., 2011; Saintilan et al., 2014).

Table 15.1. Average Values for Ecosystem Extent (km^2) by Coast (Atlantic, Pacific, Gulf of Mexico, and Arctic) for North America[a] (Includes Combined Mapped Data for Canada, Mexico, and the United States)

Coast	Tidal Freshwater Marsh	Tidal Freshwater Forest	Tidal Brackish and Saline Marsh	Tidal Brackish and Saline Forest	Total Tidal Wetland	Seagrass	Estuarine[b]
Atlantic Coast	539	1,916	7,958	768	11,181	11,889	34,000
Gulf of Mexico	1,612	1,153	9,847	9,899	22,511	20,260	31,900
Pacific Coast	83	188	510	2,642	3,423	1,148	49,000
High Latitudes	ND[c]	ND	1,494	NA[c]	1,494[d]	1,050	238,800
CONUS	2,234	3,257	18,162	3,165	26,818	23,630	75,040
Alaska	ND	ND	948	NA	948[d]	405	ND
Canada	ND	ND	546	NA	546[d]	645	ND
Mexico	ND	ND	153	10,144	10,297[d]	9,667	ND
North America	2,234[d]	3,257[d]	19,809	13,309[d]	38,609[d]	34,347	353,700

Notes

a) Geospatial data sources: CEC 2016; Laruelle et al., 2013; USFWS NWI 2017.

b) All estimates based on MARgins and CATchments Segmentation (MARCATS) data of Laruelle et al. (2013), except the conterminous United States (CONUS), which is from Bricker et al. (2007). Corresponding MARCATS segment numbers are 10 for the Atlantic Coast; 9 for the Gulf of Mexico; 1, 2, and 3 for the Pacific Coast; and 11, 12, and 13 for High Latitudes.

c) ND = no data, NA = not applicable.

d) Indicates missing data from at least one coastal subregion.

Mangroves extend all the way around GMx, with 80% of the total distribution of North American mangroves on the Mexican coastline (50% of which grow on the Campeche, Yucatán, and Quintana Roo coasts). Mangrove carbon sequestration rates can range from 0 to 1,000 g C per m^2 per year, primarily a result of biomass responses to disturbance status and hydrogeomorphic characteristics of the landscape setting (Adame et al., 2013; Breithaupt et al., 2014; Ezcurra et al., 2016; Marchio et al., 2016). Regular tidal flushing and allochthonous input from river and marine sediments generally provide more favorable conditions for above- and belowground productivity. The belowground components of mangrove forests, such as coarse woody debris, soil, and pneumatophores (i.e., aerial roots), can contribute between 45% and 65% of the total ecosystem respiration (Troxler et al., 2015). Mangroves are similar to all tidal wetlands in that soil carbon pools dominate ecosystem carbon stocks, and carbon burial is an important long-term fate of fixed carbon. For example, despite their short stature, dwarf mangroves may generate greater annual increases in belowground carbon pools than might taller mangroves (Adame et al., 2013; Osland et al., 2012).

Coupled stressors from both human and natural drivers, such as groundwater extraction and sea level rise, currently are altering subtropical tidal wetlands. Soil organic carbon (SOC) stocks face increased rates of mineralization and peat collapse with saline intrusion (Neubauer et al., 2013). Still, total carbon stocks may increase as a result of trends in mangrove expansion into salt marsh habitat (Cavanaugh et al., 2014; Doughty et al., 2015; Krauss et al., 2011; Bianchi et al., 2013). This pattern of expansion is expected to continue with current trends in climate change (e.g., the changes in frequency and intensity of hurricanes and freeze events) and with increasing rates of sea level rise (Barr et al., 2012; Lagomasino et al., 2014; Meeder and Parkinson 2017; Dessu et al., 2018). Dwarf and basin mangroves, which generally have shorter canopies, are most affected by freezing temperatures, while hurricane damage has the strongest impact on fringing mangrove forests along the coasts (Zhang et al., 2016). Freeze and cold events drive the poleward advancement of mangroves along the eastern coast of Florida and GMx (Cavanaugh et al., 2014; Giri et al., 2011; Saintilan et al., 2014). Though mangroves in these regions may not currently extend past their historical range limits (Giri and Long 2014), the expansion and contraction of the mangrove forest clearly is documented in field and remotely sensed map products.

15.3.3 Pacific Coast Estuaries and Tidal Wetlands

The Pacific (west) coast of North America is seismically active with subduction zones that create steep topography and narrow continental shelves. As such, seasonal coastal winds drive upwelling and downwelling events that can shape biogeochemical cycling along the Pacific continental margin in estuarine waters and tidal wetlands. A more descriptive approach herein reflects the limited representation of Pacific Coast information presented in Appendix 15A, p. 642, as compared with that for the Atlantic and GMx coastlines.

Pacific Coast Estuaries

Estuaries of the Pacific Coast differ from other North American estuaries in that their carbon cycle dynamics tend to be dominated by ocean-sourced rather than river-borne drivers, predisposing many Pacific Coast estuaries and coastal environments to hypoxia and acidified conditions, largely as a result of natural processes (e.g., Chan et al., 2016, 2017; Feely et al., 2010, 2012; Hales et al., 2016). From the Gulf of Alaska south through Puget Sound, glacially formed estuaries have sills that restrict circulation between estuaries and coastal waters, further predisposing deep estuarine waters to hypoxic or anoxic conditions that form in the deep water of these estuaries. Interannual-to-decadal, basin-scale, ocean-climate oscillations such as the Pacific Decadal Oscillation and El Niño Southern Oscillation drive variations in rainfall along the Pacific Coast, which, in turn, controls material export from land to estuaries and subsequently to the coastal ocean. These oscillating climate drivers, as well as stochastic events such as large marine heatwaves, drive interannual variability

in physical and biogeochemical dynamics along the Pacific Coast, with significant effects on estuarine carbon cycle and ecosystem processes (Di Lorenzo and Mantua 2016).

Within spatially large marine ecosystems (LMEs) on the Pacific Coast—Gulf of Alaska, California Current, Gulf of California, and Pacific Central-American Coastal LMEs (lme.noaa.gov)—estuaries represent either globally significant large river systems, such as the Fraser, Columbia, San Joaquin/Sacramento, and Colorado rivers or one of many "small mountainous rivers" (SMRs) with steep watershed terrain and limited continental shelves for delta development. From the Southern California Bight (SCB) south to Panama, lagoons also represent a significant fraction of the semi-enclosed, saline-to-brackish water bodies along the Pacific Coast. Lagoons typically have episodic connection to adjacent coastal ocean areas and lack substantial freshwater input, distinguishing them from estuaries. However, despite the strong along-coast gradients in rainfall and terrestrial input to Pacific Coast lagoons and estuaries, oceanic sources of nutrients and carbon, particularly those delivered via upwelling, play an important or dominant role in carbon cycle dynamics in all systems studied (Camacho-Ibar et al., 2003; Davis et al., 2014; Hernández-Ayón et al., 2007; Steinberg et al., 2010).

Terrestrial inputs to Pacific Coast estuaries vary substantially along the steep rainfall gradient from very wet conditions in the north to arid conditions in southern and Baja California, with precipitation increasing again from central Mexico through Panama. The Global NEWS 2 model estimated terrestrial TOC inputs are approximately 8.5 teragrams of carbon (Tg C) per year to the Gulf of Alaska through northern California, 0.7 Tg C per year to southern and Baja California and the Gulf of California, and 2.8 Tg C per year to Mexico south of Baja California and Central America (Mayorga et al., 2010). The SMRs representing a significant portion of these inputs are similar to the Mississippi River in delivering their freshwater, nutrient, and organic carbon loads directly to the coastal ocean or larger estuarine water bodies such as Puget Sound or the Strait of Georgia (Johannessen et al., 2003; Wheatcroft et al., 2010).

Phytoplankton productivity estimates across Pacific Coast estuaries from San Francisco Bay to British Columbia reflect an order of magnitude variation in median annual primary production rates, from about 50 g C per m^2 per year in the Columbia River estuary to 455 to 609 g C per m^2 per year in the Indian Arm fjord near Vancouver, British Columbia (Cloern et al., 2014). The role of riverborne nutrients is exemplified by the total water column primary production estimate for the Columbia River estuary at 0.030 Tg C per year (Lara-Lara et al., 1990). An air-sea CO_2 exchange study on the Columbia River estuary estimated that the net annual emission is quite small at 12 g C per m^2 per year (Evans et al., 2012). SCB estuaries are also highly productive but most likely act as sources of CO_2 to the atmosphere and net exporters of dissolved inorganic and organic carbon to the coastal ocean owing to input and decomposition of allochthonous carbon from surrounding land areas. All recent studies from lagoons and estuaries in the San Diego area report estuarine pCO_2 levels consistently greater than atmospheric levels (Davidson 2015; Paulsen et al., 2017; see also Southern California Coastal Ocean Observing System: sccoos.org/data/oa). Carbon cycling in lagoons with little or no riverine input is likely to be dominated by upwelling, as in San Quintín Bay, Baja California. Most of San Quintín Bay (85%) acts as a source of CO_2 to the atmosphere (131 g C per m^2 per year) due to the inflow and outgassing of CO_2-rich upwelled waters from the adjacent ocean. The remaining 15%, composed of *Zostera marina* seagrass beds, shows net uptake of CO_2 and bicarbonate (HCO_3^-), with pCO_2 below atmospheric equilibrium, resulting in a net CO_2 sink of 26 g C per m^2 per year (Camacho-Ibar et al., 2003; Hernández-Ayón et al., 2007; Munoz-Anderson et al., 2015; Reimer et al., 2013; Ribas-Ribas et al., 2011). Whereas this Mediterranean climate bay was net autotrophic during the upwelling season in previous decades, it now appears to be net heterotrophic due to import of labile phytoplanktonic carbon generated in the

adjacent ocean during upwelling (Camacho-Ibar et al., 2003). This transition illustrates the potential sensitivity of estuarine, bay, and lagoonal net ecosystem production (NEP) to changes in upwelling intensity and persistence, highlighting the vulnerability to effects of ocean warming or changing coastal stratification on ecosystem metabolism and carbon balance.

Lateral transfers of carbon from estuaries to the coastal ocean are poorly constrained by observations because of the difficulty and expense of making sufficient direct observations to measure this important lateral transfer. Many gaps remain in the understanding of the carbon cycle of Pacific Coast estuaries and lagoons, despite sporadic observations over the last several decades. For example, no systematic information on carbon burial is available and seagrass extent is likely undermapped (CEC 2016). With few exceptions, long-term monitoring time series are inadequate to track changes in terrestrial carbon inputs, primary production, air-sea CO_2 exchange, carbon burial in sediments, and carbon transfers to the coastal ocean that can be expected to result from climate and human-caused environmental changes (Boyer et al., 2006; Canuel et al., 2012). Implementing long-term observations of carbon, oxygen, and nutrient biogeochemistry, along with metrics of ecological response and health, in Pacific Coast estuaries is a priority (Alin et al., 2015).

Pacific Coast Tidal Wetlands

The Pacific Coast is dominated by rocky headlands, broad sand dune complexes, sand beaches, and spits (i.e., sandbars). The area of Pacific Coast tidal wetlands is roughly 628 km^2 in the United States (NOAA 2015) and at least 2,522 km^2 in Mexico, predominantly as mangroves (Valderrama-Landeros et al., 2017), perhaps more if shallow water habitats are included (Contreras-Espinosa and Warner 2004). While small but iconic "low-flow" estuaries are distributed sparsely along the coast (e.g., Elkhorn Slough and Tomales Bay), areas of expansive estuarine wetlands are limited to the larger coastal estuaries, where major rivers enter the sea and where embayments are sheltered by sandbars or headlands (e.g., Coos Bay, Humboldt Bay, and San Diego Bay). San Francisco Bay, which supports the largest extent of coastal wetlands along the Pacific Coast of North America, is a tectonic estuary—a down-dropped graben (i.e., trench) located between parallel north-south trending faults. In Mexico, coastal wetlands are found in association with large barrier-island lagoon complexes where wave energy is reduced by headlands, offshore islands, or the Baja California peninsula, as well as along the Gulf of Tehuantepec, where the continental shelf widens and the winds are intense and offshore (northerly), originating in the Gulf of Campeche across the Isthmus of Tehuantepec. Assuming that published studies of soil carbon accumulation (79 to 300 g C per m^2 per year (Ezcurra et al., 2016) are broadly representative of U.S. and Mexico coastlines, average estimates of soil carbon sequestration by Pacific estuarine wetlands sum to 0.05 Tg C per year for the United States and 2.67 Tg C per year for Mexico.

Although U.S. Atlantic and GMx coastlines are known to support more organic-rich sediments, rates of carbon burial in tidal wetlands on the Pacific Coast tend to be commensurately high due to high rates of volume gain through sediment accretion. Previous studies have reported accretion rates of 0.20 to 1.7 cm per year in natural marshes along the Pacific Coast of North America (Callaway et al., 2012; Thom 1992; Watson 2004), with many values at the higher end of this range. High rates of sediment accretion are a function of the active Pacific Coast margin, because Pacific coastal watersheds tend to have high relief and support elevated erosion rates while providing limited opportunity for deposition of sediments along lowland floodplains (Walling and Webb 1983). This circumstance leads to high water column–suspended sediment concentrations, often exacerbated by anthropogenic land-use activities, such as agriculture, grazing, logging, and development (Meybeck 2003). Although not ubiquitous due to landscape changes (e.g., Skagit River), high rates of sediment accretion are common and known to promote high carbon burial rates when allochthonous organic carbon derived from upland sources is a sediment constituent

(Ember et al., 1987). Additionally, organic carbon produced *in situ* is more quickly buried in the sediment anoxic zone in high-accumulation environments (Watson 2004).

15.3.4 High-Latitude (Alaskan, Canadian, and Arctic) Estuaries and Tidal Wetlands

High-latitude estuaries (boreal and Arctic) are the youngest estuaries (<1,000 years) but the most subject to coastal erosion and hydrological carbon export from thawing permafrost during the current warming climate. Terrigenous inputs of silt and organic carbon are estimated as dominant sources of carbon flux, but inadequate mapping and measurements limit current estimates of carbon fluxes in high-latitude estuaries and tidal wetlands.

High-Latitude (Arctic) Estuaries

Salinity gradients are a defining feature of the estuarine zones of the Arctic Ocean (McClelland et al., 2012). Further, nearshore ice conditions are changing, erosion of coastlines is increasing, and the duration and intensity of estuarine and ocean acidification events are increasing (Fabry et al., 2009), as also discussed in Ch. 16: Coastal Ocean and Continental Shelves and Ch. 17: Biogeochemical Effects of Rising Atmospheric Carbon Dioxide. Lagoons in the Alaskan Beaufort Sea, bounded by barrier islands to the north and Alaska's Arctic slope to the south, span over 50% of the coast. These lagoons link marine and terrestrial ecosystems and support productive biological communities that provide valuable habitat and feeding grounds for many ecologically and culturally important species. Beaufort Sea lagoons are icebound for approximately 9 months of the year; therefore, the brief summer open-water period is an especially important time for resident animals to build energy reserves (i.e., necessary for spawning and surviving winter months) and for migratory animals to feed in preparation for fall migrations. Recent dramatic declines in ice extent have allowed wave heights to reach unprecedented levels as fetch has increased (AMAP 2011).

These studies highlight the climate linkages along coastal margins of the Arctic, especially how changes in sea ice extent can affect terrestrial processes (Bhatt et al., 2010), controlling coastal erosion and the transport of carbon, water, and nutrients to nearshore estuarine environments (Pickart et al., 2013). Nearshore estuarine environments in the Arctic are critical to a vibrant coastal fishery (von Biela et al., 2012) and also serve as habitat for hundreds of thousands of birds representing over 157 species that breed and raise their young over the short summer period (Brown 2006).

High-Latitude (Arctic) Tidal Wetlands

High-latitude ecosystem carbon flux measurements tend to focus on abundant inland peatlands (see Ch. 11: Arctic and Boreal Carbon, p. 428, and Ch. 13: Terrestrial Wetlands, p. 507), and thus less is known about Arctic and subarctic tidal marshes. However, due to high sedimentation rates, Arctic estuarine wetlands are estimated to sequester carbon at rates up to tenfold higher per area than many other wetlands (Bridgham et al., 2006). In a North American survey of published literature, Chmura et al. (2003) accounted for soil carbon stock only to 50 cm in depth, but some brackish marshes, especially in seismically active regions, have much deeper organic sediments. The Hudson Bay Lowlands tidal marshes are a notably understudied region where soil carbon stocks in the nontidal component alone are estimated to contain 20% of the entire North American soil carbon pool (Packalen et al., 2014). Gulf of Alaska marshes are relatively low salinity or freshwater dominated due to the excess of precipitation over evapotranspiration of the Pacific Northwest, as well as the substantial glacial meltwater that characterizes the region. Still, the large impact of melting glaciers, including the Bering and Malaspina piedmont glaciers (each approximating the size of Rhode Island), is expected to contribute to sea level rise locally, as will thawing river deltas, such as the Yukon-Kuskokwim Delta, that are characterized by discontinuous permafrost.

One of the most important coastal Alaskan marsh systems is the Copper River Delta, a critical habitat

for migratory birds along the Pacific Flyway, which extends for more than 75 km and inland as much as 20 km in some places along the Gulf of Alaska (Thilenius 1990). Although carbon storage estimates in these marsh locations are lacking, extensive research on the uplifted (and buried) peats by Plafker (1965) indicate alternating events of extreme subsidence and uplift (i.e., yo-yo tectonics). For example, the 1964 earthquake raised the entire delta from 1.8 to 3.4 m (Reimnitz 1966). Current studies on peat cores reveal marsh vegetation interspersed with intertidal muds, freshwater coastal forest, and moss peat, which extends to depths greater than 7 m (Plafker 1965). Whereas geological drivers clearly are the primary control on carbon storage in these marshes, the dynamic relationship with vegetation illustrates biological feedbacks as well (e.g., nutrient redistribution; Marsh et al., 2000). Highly dynamic sedge- and rush-dominated marshes are notably resilient to extensive sediment deposition from the Copper River, further ensuring growth of willows and shrubs and contributing to the woody component of buried peats. Whether the areal extent of these wetlands will expand or decline with tectonic impact and regional sea level rise is not known.

15.4 Carbon Fluxes and Stocks in Tidal Wetlands and Estuaries of North America

Literature summaries and data compilations discussed in this section enable estimates to be made of carbon stocks and fluxes in North American tidal wetlands and estuaries. Accuracy in quantifying stocks and fluxes in tidal wetlands and estuaries is a function of the accuracy in estimated area (extent) and in estimated stocks and fluxes per unit area. For North America, estimates involve areas, sediment carbon stocks, and the following fluxes: the net change in the carbon stock of tidal wetland soils, tidal wetland exchange of CO_2 with the atmosphere (i.e., NEE), tidal wetland exchange of CH_4 with the atmosphere, tidal wetland carbon burial, lateral exchange of carbon between tidal wetlands and estuaries, and estuarine outgassing of CO_2. Additionally, because the conterminous United States (CONUS) contains a more robust estuarine dataset of most stocks and fluxes, a separate analysis is presented for this region that includes estimates of estuarine NEP, burial, and export of organic carbon to shelf waters.

15.4.1 Tidal Wetland and Estuarine Extent

A synthesis of recent compilation efforts is used to estimate the areas of tidal wetlands and estuaries, and the accuracy of these estimates varies among countries of North America (see Table 15.1, p. 604). In CONUS, a tidal wetland distribution is estimated using the full salinity spectrum of tidal wetland habitats mapped by the U.S. Fish and Wildlife Service National Wetlands Inventory (USFWS NWI; Hinson et al., 2017). However, in Mexico and Canada, only saline wetlands are available at a national scale, as mapped by the Commission for Environmental Cooperation (CEC; CEC 2016). Hence, tidal wetland areas in Mexico and Canada are likely underestimated. Estimates for the estuarine area of North America use a global segmentation of the coastal zone and associated watersheds known as MARCATS (MARgins and CATchments Segmentation; Laruelle et al., 2013). The MARCATS product is available globally at a resolution of 0.5 degrees and delineates a total of 45 coastal regions, or MARCATS segments, eight of which are in North America. Some CONUS-only applications use estuarine areas from the National Estuarine Eutrophication Assessment survey (Bricker et al., 2007), which is based on geospatial data from the National Oceanic and Atmospheric Administration (NOAA) Coastal Assessment Framework (NOAA 1985). The Coastal Assessment Framework includes a high-resolution delineation of the U.S. coastline in this area and delineates 115 individual estuarine subsystems. Seagrasses are considered separately because of their distinct sediment carbon stocks, even though they overlap in area with estuaries. Seagrass area across North America is estimated according to CEC (2016), using web-available map layers.

Table 15.1, p. 604, reveals the relative areas of tidal wetlands, estuaries, and seagrasses of North America, in addition to how these ecosystems are distributed by subregion and country. Estuaries of

North America cover about 10 times the area of tidal wetlands. About half the tidal wetlands of North America are salt marsh, a third are mangrove, and the remainder is split roughly between tidal fresh marsh and tidal fresh forest. The high-latitude region is characterized by a large estuarine area, about 60% of North America's total estuarine area, but has only a few percent of the continent's tidal wetland area and seagrass area. The Gulf of Mexico (GMx), on the other hand, is home to most of North America's tidal wetlands and seagrasses, with 58% of each. The Atlantic Coast and GMx each have about 10% of the total estuarine area, and the Atlantic coast has about half the tidal wetland area and seagrass area of GMx. The Pacific Coast is similar to the high-latitude subregion with a relatively small area of tidal wetlands and seagrasses (although these areas may be undermapped), and it has an estuarine area about 50% greater than that of GMx. Tidal wetlands of North America reside mainly in CONUS (as salt marsh) and Mexico (as mangroves). Similarly, seagrasses are found mainly in coastal waters of CONUS and Mexico. Estuarine area is not available by country, except for CONUS, which is estimated to have 21% of North America's total estuarine area.

15.4.2 Tidal Wetland and Estuarine Stocks

Estimates of tidal wetland and estuarine carbon stock in the upper 1 m of sediment or soil were made by using estimates of the carbon density (mass carbon per unit volume) from large synthetic datasets. Cross-site comparisons of soil carbon stocks in tidal wetlands illustrate very little range in carbon densities in North America both downcore and among tidal wetlands of varied salinity, vegetation structure, and soil types. Hence, for all tidal wetlands except GMx mangroves, a single estimate of carbon density, 27.0 ± 13 kg organic carbon per m^3, was used based on a comprehensive review of the literature (Chmura 2013; Holmquist et al., 2018a; Morris et al., 2016; Nahlik and Fennessy 2016; Ouyang and Lee 2014). For mangroves in GMx, a value of 31.8 ± 1.3 kg organic carbon per m^3 was used (Sanderman et al., 2018). A review of seagrass SOC densities (CEC 2017; Fourqurean et al., 2012; Kennedy et al., 2010; Thorhaug et al., 2017) revealed more variance within and between regions, with some notably high soil carbon densities in GMx. Best estimates (and ranges) of 2.0 ± 1.3 kg organic carbon per m^3 were used for the Atlantic Coast and high-latitude subregions, 3.1 ± 2.4 kg organic carbon per m^3 for GMx, and 1.4 ± 1.2 kg organic carbon per m^3 for the Pacific Coast. For organic carbon density in estuarine sediments, a carbon density of 1.0 ± 1.2 kg organic carbon per m^3 was used based on a mean value of organic carbon mass fraction (0.4% organic carbon in waters shallower than 50 m; Premuzic et al., 1982; Kennedy et al., 2010) and a dry bulk density average of 2.6 g per cm^3 from Muller and Suess (1979). The assumed carbon densities and areas led to carbon stocks in the upper 1 m of 1,410, 354, and 122 Tg C for tidal wetlands, estuaries, and seagrasses, respectively, with a total carbon stock of 1,886 ± 1,046 Tg C.

Net Change in Tidal Wetland Soil Carbon Stock

An estimate of tidal wetland carbon stock loss could only be made using the loss rate for saltwater wetlands in CONUS, as loss rates in other parts of North America and for tidal fresh wetlands are not available. However, CONUS saltwater wetlands make up the overwhelming majority of North American tidal wetlands (see Table 15.1, p. 604), so applying the CONUS saltwater wetland loss rate to all North American tidal wetlands is not unreasonable. The use of a loss rate of CONUS vegetated saltwater wetlands of 0.18% per year between 1996 and 2010 (Couvillion et al., 2017) and estimated mass of carbon in the upper meter of tidal wetland soils (i.e., 1,362 Tg C) resulted in an overall annualized loss rate of 2.4 Tg C per year. For CONUS only, which holds 1,019 Tg C, the loss rate is 1.8 Tg C per year. Expert judgement assigned 100% errors to these losses because they are deeply uncertain due to annualized episodic events (e.g., Couvillion et al., 2017), difficulty in mapping loss, and difficulty in assessing the rate and fate of carbon from disturbed tidal wetlands (Ward et al., 2017; Lane et al., 2016).

15.4.3 Tidal Wetland and Estuarine Fluxes

Tidal Wetland Net Ecosystem Exchange

Presented in Table 15A.1, p. 642, are annual estimates of NEE in North America based on

continuous measurements, focusing primarily on eddy covariance approaches and high-frequency datasets from static chamber deployments to reduce uncertainty. A total of 16 sites were compiled, including restored wetlands, all of which are in CONUS and mostly along the Atlantic Coast. This limited dataset indicates that NEE varies greatly within and among sites, ranging from the highest annual uptakes in a mangrove ecosystem (–1,200 g C per m^2 per year) to the greatest annual losses in a mudflat (1,000 g C per m^2 per year) and in a sequence of tidal marshes in Alabama (400 to 900 g C per m^2 per year; Wilson et al., 2015). Excluding the restored sites and mudflats from the Hudson-Raritan estuary in New Jersey, as well as the static chamber data from Alabama, the mean NEE at the continuously monitored sites (n = 11 of 16) was negative, indicating uptake of atmospheric CO_2 by tidal wetlands. Comparing annual values from the 11 sites (comprising 22 annual datasets) yields coast-specific estimates of NEE: –133 ± 148 g C per m^2 per year on the Pacific (one site, 3 years), –231 ± 79 g C per m^2 per year on the Atlantic (seven sites, 1 to 3 years), and –724 ± 367 g C per m^2 per year in GMx (three sites, 1 to 5 years). Integrating these estimates by area of tidal wetlands on each of North America's three coasts, the NEE estimate is –27 ± 13 Tg C per year. For CONUS only, NEE is –19 ± 10 Tg C per year.

Tidal Wetland Carbon Burial

Rates of carbon burial in wetland soils and sediments are associated with specific temporal scales depending on calculation methods. Typically, carbon burial is calculated as the product of *soil carbon density* (i.e., the mass of carbon stored in soil per unit volume) multiplied by *accretion rate* (i.e., the vertical rate of soil accrual and thus change in volume), which is measured by a variety of dating techniques that span multiple time frames (e.g., marker horizons; radioactive isotopes including those of cesium (^{137}Cs), lead (^{210}Pb), and carbon (^{14}C); pollution chronologies; and pollen stratigraphy). Carbon burial is thus a rate of carbon accumulation in tidal wetland soils over a specific time period (typical units are g C per m^2 per year). This measure integrates all carbon pools present, both "old" and "new," and both autochthonous and allochthonous sources.

Table 15.2 lists carbon burial estimates for salt marshes summarized by Ouyang and Lee (2014), excluding short-term accretion cores (e.g., marker horizons). Identified were 125 cores in North America, about half of which are along the Atlantic Coast and the rest roughly spread evenly among the three other subregions. Mean carbon burial estimates vary considerably among the four subregions, with the lowest rates along the Atlantic Coast, intermediate rates along the Pacific Coast, and the highest rates in the high-latitude subregion and GMx. The spatially integrated burial rate was computed for each subregion by multiplying its mean burial rate by its tidal wetland area, thus using an assumption that the salt marsh burial rate applies to tidal freshwater and mangrove systems. The spatially integrated burial rate (±2 standard errors) across North America is 9.1 ± 4.8 Tg C per year, with more than 75% in GMx, owing to its large tidal wetland area (see Table 15.1, p. 604) and high carbon burial rate (see Table 15.2, p. 612). For CONUS alone, assuming equivalent distributions of rates among coasts and vegetation types, carbon burial is estimated to be 5.5 ± 3.6 Tg C.

Tidal Wetland CH_4 Fluxes

While CH_4 fluxes tend to be negligible from tidal wetlands with high soil salinities, emissions can increase considerably when sulfate availability is lower (as indexed by salinity; Poffenbarger et al., 2011). Based on the higher net radiative impact of CH_4, climatic benefits of CO_2 uptake and the sequestration illustrated by most of the sites in Table 15A.1, p. 642, may be offset partially by CH_4 release in lower-salinity tidal wetlands (Whiting and Chanton 2001).

Here are reported annual CH_4 fluxes from tidal wetlands across North America (see Table 15A.2, p. 644), with values from studies published in 2011 or earlier taken from Poffenbarger et al. (2011). For studies published after 2011, the same methodology was used as Poffenbarger et al. (2011) in analyzing CH_4 flux data and reporting average annual CH_4

Table 15.2. Carbon Accumulation Rate (CAR) and Associated Data for Tidal Estuarine (Salt and Brackish) Marsh[a]

Region	n	Mean CAR ± 2σ[b] (g C per m² per year)	Regional Tidal Wetland Burial[c] ± 2σ (Tg C per year)
High Latitudes	25	301 ± 155	0.5 ± 0.2
Atlantic Coast	59	126 ± 87	1.4 ± 1.0
Pacific Coast	18	173 ± 92	0.6 ± 0.3
Gulf of Mexico	23	293 ± 210	6.6 ± 4.7
North America	125	236 ± 124	9.1 ± 4.8

Notes

a) From Ouyang and Lee (2014).

b) 2σ = 2 standard errors.

c) Regional burial calculated for all tidal wetland types regardless of salinity or vegetation type.

d) Key: n, number of sites; g C, grams of carbon; Tg C, teragrams of carbon.

emissions. If CH_4 emissions were measured over all seasons of the year with the annual rate unreported, calculations were made by extracting emission rates from tables and figures and then interpolating between time points. Finally, although this was only the case in a few studies, for short-term studies lasting a few days to months over the growing season, average daily CH_4 emissions were calculated and then converted to annual fluxes using the rate conversion factors determined by Bridgham et al. (2006). The compilation resulted in CH_4 flux measurements at 51 sites in North America.

The compilation, illustrated in Figure 15.3, this page, continues to support the role of salinity as a predictor of CH_4 emissions observed by Poffenbarger et al. (2011). However, there is considerable variability among methods and sites in annual CH_4 emissions in fresh and brackish (i.e., oligohaline and mesohaline) wetlands, indicating the need for further studies to help improve understanding of the drivers and sensitivities of CH_4 fluxes in these common salinity ranges. Tidal wetlands in the salinity range of 0 to 5 practical salinity units (PSU; i.e., fresh-oligohaline) show an average (±2 standard errors) CH_4 emission of 55 ± 48 g CH_4 per m² per year, whereas tidal wetlands in the salinity range of 5 to 38 PSU (i.e., mesohaline to fully saline) emit CH_4 at an average rate of 11 ± 13 g CH_4 per m² per year. The spatially integrated tidal wetland CH_4

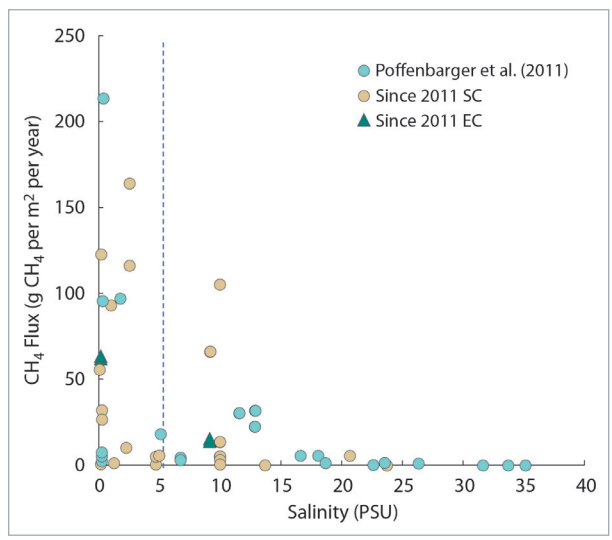

Figure 15.3. Tidal Marsh Methane (CH_4) Emissions Versus Salinity. Approaches to measuring atmospheric CH_4 flux are coded by method as SC (static chamber) and EC (eddy covariance flux tower). CH_4 flux is in grams (g); salinity is in practical salinity units (PSU). The dashed line denotes the demarcation of fresh and oligohaline marshes (0 to 5 PSU) versus mesohaline to saline marshes (5 to 35 PSU).

emission rate, computed by multiplying the fluxes for fresh-oligohaline and mesohaline-saline systems by their respective areas (5,491 and 33,118 km^2; see Table 15.1, p. 604), results in 0.29 ± 0.27 and 0.35 ± 0.43 Tg CH_4 per year, respectively, totaling 0.65 ± 0.48 Tg CH_4 per year (0.49 ± 0.36 Tg C per year) across the entire salinity gradient. Hence, in North America, fresh-oligohaline and mesohaline-saline systems contribute about equally to the total flux, with the former having high per-unit-area flux rates and low area and the latter having low per-unit-area flux rates and high area.

Lateral Fluxes of Carbon from Wetlands to Estuaries

A significant part of tidal wetland and estuarine carbon budgets is the lateral flux from tidal wetlands to estuaries, which is due mainly to tidal flushing. Twelve estimates of TOC (in both dissolved and particulate forms) exchange (per unit area of wetland) in tidal wetlands of the eastern United States were summarized by Herrmann et al. (2015), and the mean value and 2 standard errors derived in that study (185 ± 71 g C per m^2 per year) were used herein. Similarly, four estimates of DIC exchange in eastern U.S. tidal wetlands were summarized in Najjar et al. (2018), with a mean (±2 standard errors) of 236 ± 120 g C per m^2 per year. With only a small number of DIC flux measurements, the error was doubled. Hence, tidal wetland export of total carbon is estimated to be 421 ± 250 g C per m^2 per year. Applying this to all North American tidal wetlands (see Table 15.1, p. 604) yields a total export of 16 ± 10 Tg C per year; applied to CONUS wetlands only, the estimate of lateral export is 11 ± 7 Tg C per year.

Estuarine CO_2 Outgassing

The SOCCR2 assessment used the global synthesis of Chen et al. (2013), which combined field estimates of outgassing per unit area with the MARCATS areas. Most MARCATS segments were found to be sources of CO_2 to the atmosphere, with the integrated flux over North America at +10 Tg C per year (see Table 15.3, this page). Chen et al. (2013) did not provide error estimates, so expert judgment was used to provide a range. The MARCATS segments in North America contain only 25 individual flux estimates, 15 of which are along the Atlantic coast, and some segments have no measurements at all (in which case data from similar systems were used). There is a possibility of a 100% error in the North American flux, so the estimate was placed at 10 ± 10 Tg C per year. Reduced uncertainty may be possible for distinct regions, but this level of error indicates confidence bounds at a continental scale.

A separate estimate was made of CONUS estuarine outgassing based on the SOCCR2 synthesis of CO_2 flux estimates (see Table 15A.3, p. 647) and the areas from the Coastal Assessment Framework (NOAA 1985). Because only one study was

Table 15.3. Estuarine CO_2 Outgassing for North America[a,e]

MARCATS[b] Segment No.	CO_2 Outgassing[c] (g C per m^2 per year)	Number of Systems	CO_2 Outgassing (Tg C per year)
1	129	3	4.4
2	11	3	0.1
3	174	0	1.1
9	96	2	3.1
10	118	15	4.0
11	–9	1	–0.3
12	–5	1	–0.2
13	–13	0	–2.1
Total North America		25	10.0
Approximate CONUS[d] (2, 9, and 10)		20	7.2

Notes

a) Based on the Global Synthesis of Chen et al. (2013).

b) MARCATS, MARgins and CATchments Segmentation.

c) For regions 3 and 13, where no data were available within the segments, the methods of Chen et al. (2013) were used.

d) CONUS, conterminous United States.

e) Key: CO_2, carbon dioxide; g C, grams of carbon; Tg C, teragrams of carbon.

identified for the Pacific Coast, analysis was limited to the Atlantic and GMx coasts, which contain about 90% of the CONUS estuarine area (see Table 15.1, p. 604). For the Atlantic coast, mean fluxes were first estimated in each of three subregions (GOM, MAB, and SAB) before multiplying by their respective areas. This was done because the outgassing per unit area increases toward the south. This analysis results in an outgassing of 10 ± 6 Tg C per year (best estimate ±2 standard errors), which is larger (but not significantly so) than the Chen et al. (2013) analysis for the three segments covering CONUS (i.e., 7 Tg C per year). The SOCCR2 synthesis is an improvement over Chen et al. (2013) by being based on a larger flux dataset and more accurate CONUS estuarine areas.

Estuarine CH_4 Emissions

Only a very limited number of studies are known to be available and scalable for estimating net CH_4 emissions in North American estuaries. In their global review, Borges and Abril (2011) report only three within North America (de Angeles and Scranton 1993; Bartlett et al., 1985; Sansone et al., 1998), ranging from 0.16 to 5.6 mg CH_4 per m^2 per day. Two recent studies with continuous sampling illustrate temporal and spatial variability. Relatively high emissions were observed in the Chesapeake Bay during summer (28.8 mg CH_4 per m^2 per day; Gelesh et al., 2016). In the Columbia River estuary (Pfeiffer-Herbert et al., 2016), summer emissions were estimated at 1.6 mg CH_4 per m^2 per day; 42% of the CH_4 losses were to the atmosphere, 32% were to the ocean, and 25% were to CH_4 oxidation. When scaled to a year, the estuarine CH_4 fluxes from the above studies range from 0.04 to 8 g C per m^2 per year, which is well below typical CO_2 outgassing rates (e.g., the U.S. Atlantic Coast mean estuarine CO_2 outgassing rate is 104 ± 53 g C per m^2 per year, see Table 15A.3, p. 647). Thus, estuarine CH_4 outgassing is likely a small fraction of estuarine carbon emissions. To be comparable with North American tidal wetland CH_4 emissions (~0.5 Tg CH_4 per year), the mean estuarine CH_4 emissions rate would need to be a conceivable rate of ~0.1 g CH_4 m^2 per year. Unfortunately, the lack of estuarine CH_4 emissions data for North America—and any well-constrained relationship with salinity or other physical parameter—precludes the possibility of making a constrained estimate of estuarine CH_4 emissions for North America.

15.4.4 Total Organic Carbon Budget for Estuaries of the Conterminous United States

The empirical model of Herrmann et al. (2015) was applied to quantify the TOC budget for CONUS estuaries (see Table 15.4, this page). This

Table 15.4. Estuarine Areas and Organic Carbon Regional Budgets for the Conterminous United States[a,c]

Estuary	Area (km^2)	Riverine + Tidal Wetland Input (Tg C per year)	Net Ecosystem Production (Tg C per year)	Burial (Tg C per year)	Export to Shelf (Tg C per year)
Gulf of Mexico	30,586	12.6 ± 3.5	−2.2 ± 0.6	−0.3 ± 0.1	−10.1 ± 3.5
Pacific Coast	6,690	1.4 ± 0.2	0.0 ± 0.2	−0.2 ± 0.1	−1.2 ± 0.2
Atlantic Coast	37,764	5.5 ± 1.3	−1.8 ± 1.0	−0.5 ± 0.3	−3.2 ± 1.3
CONUS[b]	75,040	19.5 ± 3.8	−4.0 ± 1.2	−1.0 ± 0.3	−14.5 ± 3.7

Notes

a) Positive values = input of organic carbon to estuaries; negative values = removal of organic carbon from estuaries. Source: model of Herrmann et al. (2015).

b) CONUS, conterminous United States; best estimate and ±2 standard errors.

c) Key: Tg C, teragrams of carbon.

model takes carbon and nitrogen inputs from a data-constrained watershed model and uses empirical relationships to compute burial and NEP. TOC export to shelf waters is computed by the difference. TOC input from rivers and tidal wetlands to CONUS estuaries is estimated to be 19.5 Tg C per year, with an average of 79% coming from rivers and the rest from tidal wetlands (not shown). Most of the input (74%) is exported from the estuary to the shelf, while 21% is remineralized to CO_2 and 5% is buried in estuarine sediments. Like most estuaries worldwide (Borges and Abril 2011), CONUS estuaries are, in the aggregate, net heterotrophic. However, there are regional differences in NEP, with GMx estuaries remineralizing twice as much of the TOC input as Atlantic estuaries and Pacific estuaries metabolically neutral.

15.4.5 Summary Budgets for Tidal Wetlands and Estuaries

The individual flux estimates above were combined into overall carbon budgets for tidal wetlands and estuaries of CONUS and the rest of North America. CONUS (see Figure 15.4a, this page) has better constraints on the fluxes. Central estimates of CONUS tidal wetland carbon losses and gains are very close to balancing even though they were estimated independently; burial, lateral export, and loss of soil carbon stock are all found to be significant terms of carbon removal that balance carbon uptake from the atmosphere. For the estuarine CONUS balance, riverine carbon delivery at the head of tide was taken from Ch. 14: Inland Waters (41.5 ± 2.0 Tg C per year). Including the tidal wetland delivery (11 ± 7 Tg C per year), CONUS estuaries thus were found to receive a total of 53 ± 7 Tg C per year from upland sources. With about 15% (best estimate) of this input outgassed and only a few percent buried, the resulting net total carbon flux from estuaries to shelf waters is 40 ± 9 Tg C.

The North American carbon budget for tidal wetlands and estuaries (see Figure 15.4b, this page) is similar to the CONUS budget except that most of the fluxes are larger. The net uptake of atmospheric CO_2 by the combined system of tidal wetlands and estuaries is

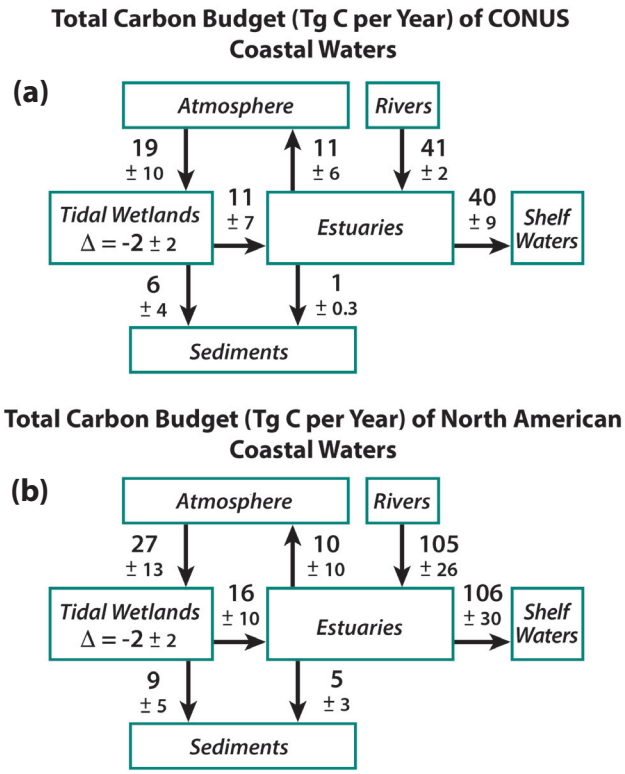

Figure 15.4. Summary Carbon Budgets for Tidal Wetlands and Estuaries. Budgets are given in teragrams of carbon (Tg C) for **(a)** the conterminous United States (CONUS) and **(b)** North America, with errors of ± 2 standard errors.

17 ± 16 Tg C per year. The riverine flux of 105 Tg C per year from Ch. 14: Inland Waters was used and assigned an error of 25%. Lacking direct estimates of carbon burial in North American estuaries, the CONUS estimate was used (see Table 15.4, p. 614) and scaled to all North American estuaries; the error is doubled to reflect this extrapolation. The carbon flux from North American estuaries to the shelf waters, estimated as a residual, is 106 ± 30 Tg C per year.

15.5 Indicators, Trends, and Feedbacks

All indications suggest that most North American coastal and estuarine environments, from Canada to Mexico, are changing rapidly as a result of global- and local-scale changes induced by climate alteration and human activities. The sustainability and quality of

estuarine and intertidal wetland habitats, including the magnitude and direction of carbon fluxes, are uncertain, especially due to limited monitoring time series relevant to changing extents and conditions of these habitats. Simulation models have illustrated the long-term sensitivity of coastal carbon fluxes to land-use and management practices while decadal and interannual variations of carbon export are attributable primarily to climate variability and extreme flooding events (Ren et al., 2015; Tian et al., 2015, 2016). Further, tidal wetland sustainability is strongly influenced by human modifications that generally reduce resilience (e.g., groundwater withdrawal, lack of sediment, nutrient loading, and ditching; Kirwan and Megonigal 2013).

Climatic changes affect entire watersheds, so the integration of small changes to terrestrial carbon cycling leads to a significant impact on the quantity, quality, and seasonality of riverine inputs to coastal zones (Bergamaschi et al., 2012; Tian et al., 2016). Within wetlands, accelerating sea level rise and increasing temperature yield a range of responses from enhanced wetland flushing, salinity intrusion, and productivity to enhanced respiration, tidal carbon export, and CH_4 emissions, which have all been postulated. Increased rates of sea level rise may enhance sedimentation and carbon burial rates up to a threshold of marsh resilience, above which erosion processes will dominate (Morris et al., 2016). This effect of accelerated sea level rise on morphology also affects carbon fluxes in shallow estuaries, whereby the loss of barrier islands to erosion will increase tidal mixing.

Estuaries show significant regional drivers of carbon cycling, such as the dominance of land-use change in Atlantic coast (Shih et al., 2010) and GMx (Stets and Striegl 2012) watersheds. In Pacific coast estuaries, ocean drivers (i.e., upwelling patterns) and rainfall variability are dominant controls on carbon fate and CO_2 degassing from Alaska to Mexico. In Arctic regions, along both Pacific and Atlantic coastlines, ice-cover melt and permafrost thaw appear to be critical drivers of wetland extent and estuarine mixing. Tidal wetland carbon dynamics, however, show more local variability than regional variability, with multivariate drivers of extent and carbon fluxes, such as sediment supply (Day et al., 2013), nutrient supply (Swarzenski et al., 2008), tidal restrictions (Kroeger et al., 2017), and subsurface water or hydrocarbon withdrawal (Kolker et al., 2011). These coastal drivers illustrate the complexity of projecting carbon fluxes and their potential to alter fundamental habitat quality. For example, estuarine acidification is observed along all coastlines with potential stress to shell fisheries (Ekstrom et al., 2015), often with changes in riverine input, circulation, and local biological dynamics more significant than direct atmospherically driven ocean acidification (Salisbury et al., 2008).

Thus, expected changes in climate and land use for the remainder of this century likely will have a major impact on carbon delivery to and processing in tidal wetlands and estuaries. While terrestrial carbon loads likely will continue to drive ecosystem heterotrophy, extreme flooding events might shunt material directly to the continental shelf, thus decreasing processing, transformation, and burial in the estuary and tidal wetlands. Overall, estuarine area likely will increase relative to that of tidal wetlands (Fagherazzi et al., 2013; Mariotti and Fagherazzi 2013; Mariotti et al., 2010), and estuarine production will become more based on phytoplankton relative to benthic algae and macrophytes (Hopkinson et al., 2012). While this trajectory may be reversible (see Cloern et al., 2016), by the end of this century tidal wetland and estuary net CO_2 uptake and storage as organic carbon quite likely will be significantly reduced throughout the United States due to passive and active loss of tidally influenced lands.

15.5.1 Observational Approaches

Coastal observations of carbon stocks and fluxes cross many spatial and temporal scales because of their intersection in multiple contexts: past or future, land or ocean, and managed or unmanaged. A variety of observational approaches has been applied to study tidal wetland habitats and carbon fluxes and exchanges with the atmosphere and adjacent estuarine and ocean waters. Currently

lacking is a standardized, consistent methodology on carbon-relevant wetland mapping, wetland carbon flux monitoring, and repeated assessment. Wetland mapping, inventories, and sampling efforts include the National Wetlands Inventory (USFWS NWI 2017), a national effort to map and classify the wetland resources in the United States (data updated at a rate of 2% per year), using aerial photography and high spatial resolution remote-sensing color infrared imagery. Light detection and ranging, or LIDAR, imagery has been applied to develop high-resolution digital elevation models for wetlands and incorporate those maps into coastal resilience (NOAA 2015) and response mapping (USGS 2018). Satellite optical (e.g., Landsat; see Appendix C: Selected Carbon Cycle Research Observations and Measurement Programs, p. 821) and synthetic aperture radar (SAR) imagery has been used for decades in mapping wetland structure and biomass, with tidal hydrologies potentially interpretable through repeat measures. High-resolution satellite ocean color observations can be used to examine wetland impacts on estuarine carbon dynamics and stocks, which, combined with hydrodynamic models, may provide information on lateral fluxes and wetland contributions to estuarine and coastal carbon budgets, especially in the actively restoring Mississippi-Atchafalaya River Delta. However, existing remote-sensing algorithms could be improved, adding the capability for representing and quantifying carbon-related properties in highly turbid estuarine and nearshore waters (Son et al., 2014). Various ground-based approaches have been applied to validate mapped carbon stocks and inventories. Deep soil cores provide quantification of carbon stocks and, when dated, can provide long-term rates of net carbon accumulation or loss (Callaway et al., 2012). Exchanges of CO_2 and CH_4 between wetlands and the atmosphere have been measured historically using static (closed) chamber systems, but, increasingly, continuous eddy covariance approaches are being deployed (Forbrich and Giblin 2015; Knox et al., 2018). Continuous gas flux measurements (i.e., NEE) over a range of temporal scales (hours to days to seasons to years) can be very effective at quantifying photosynthesis and respiration in tidal wetlands. An example of observational NEE data from estuarine ecosystems is illustrated in Figure 15.5a, p. 618. Similarly, in Figure 15.5b, p. 618, observational NEE from a tidal wetland ecosystem is shown. Estuarine NEE is typically quantified using measurements of the gradient in partial pressure across the air-water interface in combination with a model of the gas transfer velocity; more direct approaches are needed to reduce uncertainty (e.g., McGillis et al., 2001; Orton et al., 2010). Deployment of automated water quality sondes and optical sensors within channels of tidal wetlands provides a method for continuous bidirectional measurements of physicochemical and optical parameters that can be used as proxies for hydrological carbon concentrations and flux (Wang et al., 2016). These findings emphasize the importance of time-series measurements to provide *in situ* measurements of variability across timescales.

15.5.2 Modeling Approaches

While there have been numerous applications of three-dimensional estuarine biogeochemical models (Azevedo et al., 2014; Feng et al., 2015; Ganju et al., 2012; Irby et al., 2016; Kenov Ascione et al., 2014), none specifically allow integration with hydrological exchange of tidal wetlands. With unstructured meshes that provide topological flexibility, the Finite Volume Community Ocean Model (FVCOM; Chen et al., 2003) and the Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM; Ye et al., 2016, 2018) have been successfully applied to wetland-estuarine environments. Currently, there are no biogeochemical models that include accurate parameterizations for the sources and sinks that drive variability in carbon fluxes, amount, and quality at the wetland-estuary interface (e.g., allochthonous sources, photochemical transformation, and viral lysis). Further, coupled biogeochemical-geomorphic models are necessary for full tidal wetland carbon accounting and projection with accelerated sea level rise, but they have yet to be validated successfully (Kirwan et al., 2010). Efforts to

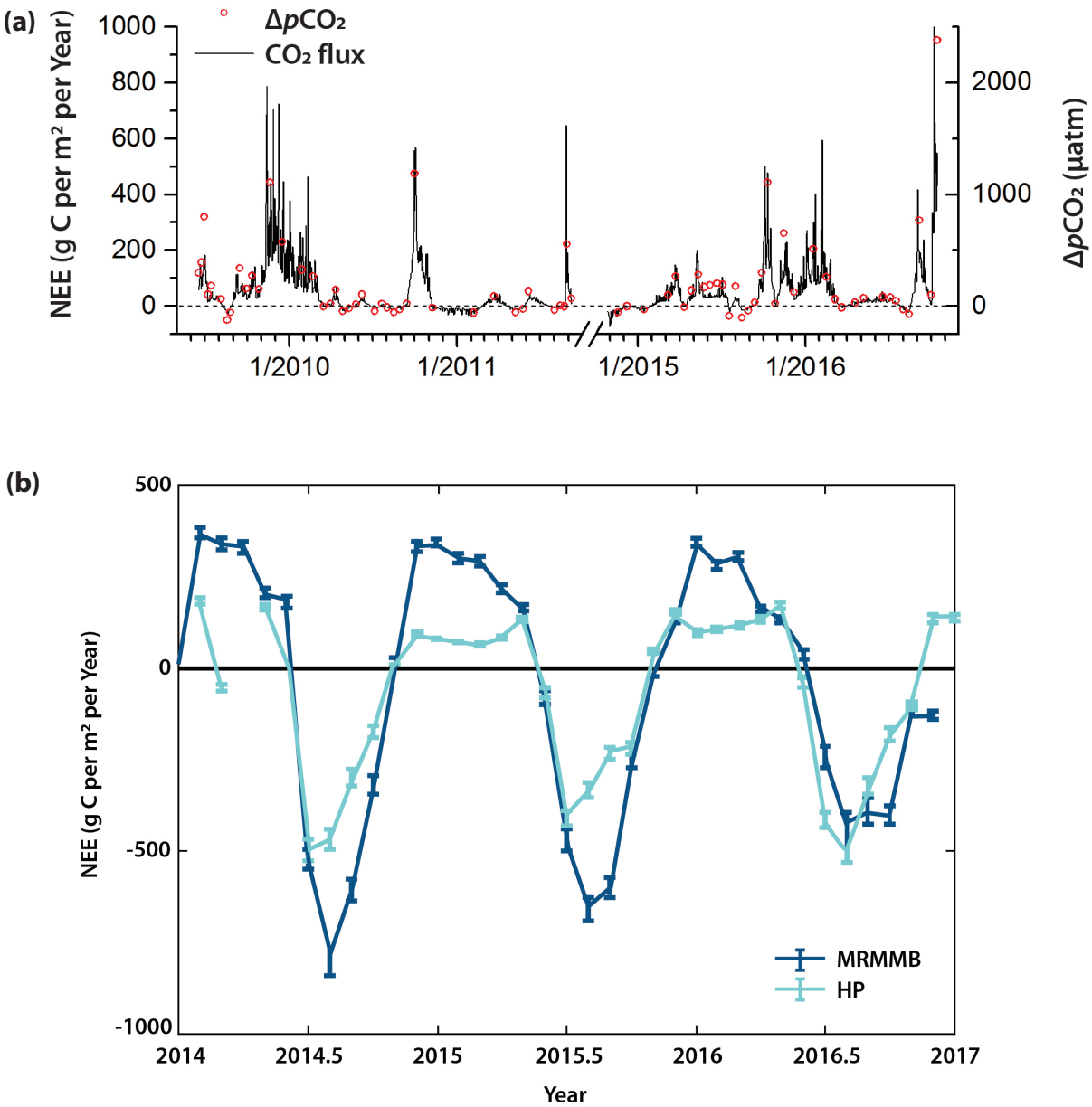

Figure 15.5. Example Observational Net Ecosystem Exchange (NEE) Data from (a) an Estuarine Ecosystem and (b) a Tidal Wetland Ecosystem. (a) NEE of carbon dioxide (CO_2, black line) and the partial pressure difference of CO_2 (ΔpCO_2) between air and water (red circles) in the Neuse River Estuary in North Carolina. NEE is positive when flux is from the water to the atmosphere. The ΔpCO_2 is positive when water pCO_2 is greater than atmospheric pCO_2. Fluxes were estimated using the pCO_2 measured during spatial surveys (Crosswell et al., 2012, 2014; Van Dam et al., 2018) and a gas transfer parameterization based on local wind speed (Jiang et al., 2008). These studies present alternative gas transfer parameterizations and associated errors. **(b)** Data are from restored coastal tidal wetlands in the New Jersey Meadowlands. The dark blue line represents the Marsh Resource Meadowlands Mitigation Bank (MRMMB; Duman and Schäfer, 2018), and the teal line, the Hawk Property (HP) natural wetland. Error bars are standard deviation of the mean of all measurements during this period (monthly). Key: g C, grams of carbon; µatm, microatmospheres.

couple tidal wetland lateral exchanges with estuarine dynamics are ongoing.

Empirical approaches to modeling include synthetic cross-site comparisons and relationships. The National Wetlands Condition Assessment (U.S. EPA 2016) illustrates homeostasis among tidal wetland soil carbon densities spatially and downcore (Nahlik and Fennessy 2016). National Aeronautics and Space Administration (NASA) synthesis efforts, which include the Wetland-Estuary Transports and Carbon Budgets (WETCARB; NASA 2017b) project and the Blue Carbon Monitoring System (Blue CMS; NASA 2017a) project, have integrated literature-derived field data and national datasets (e.g., USFWS and U.S. Department of Agriculture) and identified key differences and similarities among tidal wetland and estuarine processes for CONUS. These approaches provide boundary conditions for new observations and identify critical knowledge gaps.

Key areas to aid further research and development are:

- Mapping approaches that characterize key drivers of tidal carbon accounting (organic carbon burial and CH_4 production), such as multiple salinity classes, relative elevations, and tidal boundaries;
- Unbiased, landscape-level sampling protocol to quantify sediment carbon stock change in tidal wetlands (similar to U.S. Forest Service Forest Inventory Analysis approaches for carbon accounting);
- Remote-sensing capability suitable for highly turbid estuarine waters;
- Networks for continuous measurements of wetland-atmosphere exchanges (CO_2 and CH_4 emissions) and wetland-ocean exchanges (dissolved and particulate carbon fluxes) and better constraint and linkage of these important fluxes;
- New biogeochemical models that account for critical processes at the wetland-estuary interface, both ocean drivers (sea level rise) as well as watershed influences (land use); and
- Estuarine gas flux monitoring, including CO_2 and CH_4, especially in large, undersampled, episodic or rapidly changing environments, such as high latitudes (Arctic).

15.6 Societal Drivers, Impacts, and Carbon Management

As land- and freshwater-use changes have an outsized effect on estuarine carbon dynamics, societal drivers are at the heart of future projections for coastal zone carbon cycling. Dissolved carbon inputs are thought to have increased over the past century to Atlantic and GMx estuaries through riverine delivery, largely as a result of agricultural developments (Raymond et al., 2008; Tian et al., 2016). Similarly, delivery of nutrients from agricultural or urban growth and intensification can stimulate primary production in surface waters and respiration in bottom waters, leading to hypoxia and acidification in subsurface estuarine habitats (Cai et al., 2011; Feely et al., 2010; Irby et al., 2018). These human inputs reflect potential pathways for carbon management within estuaries by state, local, or provincial agencies and stakeholders (Chan et al., 2016; Washington State Blue Ribbon Panel on Ocean Acidification 2012). One step removed from carbon are the rich biological resources that have supported human populations on North American estuaries for millennia (e.g., Jackley et al., 2016), which link carbon management to fisheries and ecosystem management processes more broadly (Cooley et al., 2015). As ocean warming and CO_2 uptake drive changes in estuarine circulation, metabolism, and biogeochemistry, myriad changes to estuarine carbon cycles are expected over both short and long timescales, with impacts ranging from direct effects on individual species of ecosystem or economic importance to indirect effects on human health and livelihoods through stimulation of disease vectors (Bednarsek et al., 2017; McCabe et al., 2016; Waldbusser et al., 2014). Broad thinking about societal drivers of carbon cycle change and its ecosystem impacts, as well

as building effective partnerships with diverse stakeholders, will be critical to effective management of estuarine carbon cycle problems over the coming decades (DeFries and Nagendra 2017).

Coastal wetlands in temperate and tropical latitudes are a "directly or indirectly" managed landscape component, with increasing pressures from human stressors and sea level rise. Given their role in linking land, ocean, and atmospheric carbon fluxes, the increasing rate of global wetland loss and degradation is concerning. Tidal wetland areas in the United States have recently experienced relatively low rates of conversion and loss: ~0.2% per year, according to NOAA Coastal Change and Analysis Program (C-CAP) data from 1996 to 2010, with 92% of all loss occurring in Louisiana (Couvillion et al., 2017; Holmquist et al., 2018b). However, direct and indirect conversions of tidal wetlands to drained or impounded land uses continue actively along coastlines globally. In Mexico, 10% of mangrove area has been lost from 1980 to 2015, resulting in CO_2 emissions ranging from 0.4 to 1 Tg C per year (Troche-Souza et al., 2016); while GMx has more mangrove area, loss is high on the Pacific Coast due primarily to anthropogenic land-use changes.

Coastal "blue carbon" ecosystems—tidal marshes, mangroves, and estuarine sea grasses—are characterized by high areal rates of carbon sequestration, low rates of CH_4 and nitrous oxide (N_2O) emissions, and large soil carbon pools (Howard et al., 2017). Because the influence of coastal ecosystems on carbon cycles greatly exceeds their area (Najjar et al., 2018), activities that affect the conservation, degradation, or restoration of these ecosystems have implications for greenhouse gas (GHG) emissions and national GHG accounting (Kennedy et al., 2014). Loss of tidal hydrology likely shifts tidal wetlands from sinks to sources as large soil carbon reservoirs in tidal wetlands can become large sources of CO_2 emissions when disturbed (Pendleton et al., 2012), and freshwater dominance can dramatically impact CH_4 emissions (Kroeger et al., 2017). Further, nitrate pollution can dramatically impact N_2O emissions (Moseman-Valtierra et al., 2011).

In 2013, the Intergovernmental Panel on Climate Change (IPCC) issued guidance on including management of seagrasses, tidal marshes, and mangroves as an anthropogenic carbon flux in national GHG inventories (Kennedy et al., 2014). Currently a number of countries, including the United States, are in the process of implementing these guidelines (U.S. EPA 2017), an action which would be a major step toward reducing uncertainties in national carbon budgets and understanding the roles played by coastal tidal wetland management in national GHG emissions. This new information includes the relatively strong long-term sink for carbon in tidal and subtidal wetland soils, relatively limited CH_4 emissions in saline wetlands, and relatively large GHG emissions associated with wetland loss. In addition to improved knowledge of tidal wetland carbon balance, inclusion of tidal wetlands in the U.S. national GHG inventory provides an opportunity for enhanced estimation of the ecosystem services these wetlands offer to coastal communities. Ongoing research on feedbacks among hydrology, geomorphology, nutrient availability, plant productivity, and microbial activity is needed to understand and manage the impacts of human activities on the GHG balance of these ecosystems.

15.7 Synthesis, Knowledge Gaps, and Outlook

The CCARS synthesis report (Benway et al., 2016) is the most comprehensive attempt to develop a science plan for carbon cycle research of North American coastal systems. While clarifying key regional differences in processes and projections, this synthesis effort also exposed major knowledge gaps and disconnects between measurement and modeling scales. These knowledge gaps are currently being explored by multiple synthesis efforts, and below is a review of some of the major gaps being investigated.

15.7.1 Lateral Exchanges Between Tidal Wetlands and Estuaries

Estimates of lateral fluxes of carbon between tidal wetlands and estuaries are mostly based on discrete sampling events at monthly to seasonal intervals,

with sampling resolution from hourly to one half of a tidal cycle, leaving the majority of time unsampled and thus requiring large interpolation between sampling events and producing substantial uncertainty in export fluxes (Downing et al., 2009; Ganju et al., 2012). A recent estimate of the DIC lateral flux from a pristine intertidal wetland marsh on Cape Cod, Massachusetts, with minute-scale resolution revealed that previous estimates of marsh DIC export—such as those summarized by Najjar et al. (2018) and used here—may be severalfold too low (Wang et al., 2016). Previous studies generally show a positive carbon export from tidal wetlands to estuaries but may not fully resolve the export magnitude and temporal heterogeneity, which, in turn, are controlled by variability in water flux and constituent concentration across timescales from minutes to tidal cycles to years. Such observational gaps extend beyond DIC to include DOC and particulate organic carbon (POC) as well. In particular, the fate of exported POC from eroding marshes, though virtually unknown, is important for carbon accounting. Future studies should be directed to capture appropriate temporal scales of variability of carbon exports from marshes to accurately constrain lateral exchanges.

15.7.2 Coastal Subhabitat Boundaries

The definition of estuarine subhabitat within the coastal ocean is fluid, primarily associated with bottom depth and mixing processes. This boundary may not be mappable, but the absence of a robust definition inhibits future monitoring efforts and projections. Progress has been made in defining estuaries and quantifying their fundamental characteristics (such as residence time) in CONUS via NOAA's Coastal Assessment Framework (NOAA 2017). Such a framework has been essential for scaling up carbon and nitrogen fluxes from limited data (Herrmann et al., 2015; Najjar et al., 2018) and is greatly needed for all of North America. The global estuarine delineation based on MARCATS (Project Geocarbon 2017) has been very helpful, but the coarse resolution (i.e., 0.5 degrees) is a concern. For coastal wetland boundaries, multiple criteria have been used by different entities: political boundaries, salinity gradients, elevation thresholds, and tidal criteria. This variability has led to great confusion in the literature (e.g., Lu et al., 2017), in agency policies, and in market-based carbon accounting protocols. A strong gap is the lack of a boundary mapped for head of tide. Tidal wetlands, by definition, cross a wide range of salinities (i.e., saline, brackish, and freshwater), with the singular distinction of having a hydroperiod influenced by ocean tides (paraphrased from web link; U.S. EPA 2016). Networks of available data may be useful in monitoring this boundary, as it is a key distinction of carbon dynamics in coastal habitats. These networks include, for example, a NOAA repository of coastal LIDAR; NOAA tide gauge networks; USFWS wetland mapping efforts; and USGS Land Change Monitoring, Assessment, and Prevention (LCMAP; USGS 2017). In the absence of a mapped boundary, spatial accounting of tidal and estuarine extent—current, past, and future—is fraught with uncertainty, with a likely underestimate of at least 50% for freshwater tidal wetlands alone.

15.7.3 Spatial Variability in Burial Rates and in Air-Water Flux

Because of ocean influences and similar processes along coastlines, spatial variability can be much greater within an estuarine and tidal wetland complex than among regions. Tracking the drivers of spatial variability in ecosystem properties—sea level, bathymetry, river flow, elevation, soil properties, and vegetation types—can greatly improve the use of remotely sensed data to validate carbon flux models and their variability between years. Accounting processes generally rely on spatial data, and mapping stocks and fluxes in these spatially dynamic habitats will require improved use of geospatial datasets and, thus, improved attribution of location information with observations. Relative sea level rise is particularly variable in its magnitude and influence. Geomorphic models (e.g., Kirwan and Megonigal 2013; Morris et al., 2016) are improving understanding of the sustainability of wetland carbon storage, showing enhanced carbon sequestration under modest

increases in sea level but rapid carbon emissions after wetland accretion reaches its conditional "tipping point." Empirically, many GMx wetlands undergoing land subsidence appear to have crossed their threshold of sustainability and are being rapidly eroded or drowned (Couvillion et al., 2017).

15.7.4 Other Greenhouse Gases: CH_4 and N_2O

The bulk of data on CH_4 and N_2O fluxes in tidal wetlands is modeled from pore-water measurements in profile or from atmospheric chamber measurements under static conditions. However, these methods generate an incomplete picture of these dynamic environments and fluid boundaries. The growing network of eddy covariance and other continuous data-rich approaches ("movies" instead of "snapshots") is improving the understanding of the episodic nature of these processes and emergent thresholds of concern. Nitrous oxide fluxes likely are heightened under enhanced nitrate runoff (i.e., "nitrate saturation"; Firestone and Davidson 1989), but documentation is poor. Further, CH_4 production is likely low when sulfate is available (Poffenbarger et al., 2011), but it is enhanced by increased carbon fixation, such as through global changes that include rising atmospheric CO_2 concentrations or invasions of more productive species (e.g., *Phragmites australis*; Martin and Moseman-Valtierra 2015; Mueller et al., 2016).

Estuarine CH_4 emissions currently appear to be a small fraction of global emissions (i.e., <1%; Borges and Abril 2011), but they may be poised to increase with enhanced rates of methanogenesis in response to organic matter inputs and hypoxia expansion under future conditions (Gelesh et al., 2016). A seaward decrease in near-surface porewater concentrations of CH_4 is observed often, likely due to both increasing sulfate availability and *in situ* water column oxidation. Water column CH_4 and pCO_2 are positively correlated in well-mixed estuaries, suggesting *in situ* production from organic matter transferred from surface waters to methane-producing bottom waters (Borges and Abril 2011). Like tidal wetlands, many estimates of emission rates are modeled from profiles of surface and porewater concentrations of CH_4, but continuous sampling and eddy covariance data likely will reduce uncertainty in emissions and allow better characterization of the physical and biogeochemical processes associated with atmospheric CH_4 emissions.

15.7.5 Regional Gaps

Much assessment has been focused on estuaries along different regions of the Atlantic Coast (e.g., GOM, MAB, and SAB), but modeled carbon fluxes for large estuaries still remain poorly constrained. For example, few measurements of air-water CO_2 flux are available for upscaling within the Chesapeake Bay, the largest East Coast estuary (e.g., Cai et al., 2017).

The Gulf of Mexico also is well studied, but it has surprisingly few gas flux measurements in its tidal wetlands and estuaries (see, however, Holm et al., 2016). One of the most extensive regional monitoring programs, Louisiana's Coastwide Reference Monitoring System (CRMS 2017), supports GMx soil and vegetation stock change assessments and predictive models through annual records of tidal wetland conditions. These data also help illustrate the wide within-watershed variability in conditions, such as land subsidence (Jankowski et al., 2017), that drive organic carbon accretion, erosion, and mineralization processes. In addition, the Texas Commission on Environmental Quality (TCEQ) has been maintaining quarterly measurements of total alkalinity and pH in all coastal estuaries across the state in the northwestern GMx since 1969 (TCEQ 2017). This dataset may offer insight on multidecadal changes in CO_2 flux that await further investigation.

In contrast, Pacific Coast estuaries lack published carbon cycle measurements with sufficient resolution and duration to afford insight into short- or long-term changes associated with climate or human-caused forcing. Observation and modeling gaps are notably large in the Gulf of Alaska and Central American isthmus regions. For instance, very few studies have addressed CO_2 cycling and air-sea

exchange in lagoons (Ávila-López et al., 2017), a dominant habitat type in the tropical Pacific and the Gulf of California in Mexico. Estimates of air-sea exchange of climate-reactive gases (e.g., CO_2, CH_4, and N_2O) in open waters of Pacific Coast estuaries, along with estimates of primary production and carbon burial, are insufficient for a systematic analysis.

Finally, high-latitude estuaries are experiencing rapid shifts in salinity and seasonality, making relationships between climatic drivers difficult to assess. Some clear data needs for a monitoring framework in Arctic systems include depths of coastal peats along rivers, the sensitivity of productivity to rising temperatures and longer growing seasons, terrestrial carbon fluxes (including DOC and DIC), and the long-term prognosis for coastal erosion rates due to relative sea level rise.

Carbon stock and flux data from Pacific Islands, Puerto Rico, and Hawai'i are not included in this chapter because of their limited datasets (Fagan and MacKenzie 2007; MacKenzie et al., 2012) and the inability to extrapolate their data in space and time. Emerging carbon assessments may be useful for upscaling (Selmants et al., 2017), but the necessary measurements are lacking to estimate carbon fluxes of similar confidence as reported herein for continental coastlines. Hence, there is a clear need for studies of carbon cycling in the coastal environments of Pacific Islands, Puerto Rico, and Hawai'i.

15.7.6 Outlook and Conclusion

Current outlooks and understanding of tidal wetland and estuarine carbon cycling are represented herein, recognizing that synthetic and novel research activities are ongoing. The current state of knowledge represented is sufficient to identify predictable processes and responses, but uncertainty in modeling is higher when applied at continental scales and across datasets of varied confidence. Whereas coastal habitats have distinct responses to myriad global changes, regional and temporal drivers of carbon exchanges and internal processing remain critical knowledge gaps. Monitoring advances, such as high-frequency field data, remotely sensed imagery, and data integration platforms, may shed light on the carbon dynamics at the land-ocean margin and provide the clarity needed to close continental-scale carbon budgets. Improved confidence in projected changes of coastal carbon storage and processing is needed for contributing to more effective policy and management decisions in coastal communities and nationally within North America.

SUPPORTING EVIDENCE

KEY FINDING 1

The top 1 m of tidal wetland soils and estuarine sediments of North America contains 1,886 ± 1,046 teragrams of carbon (Tg C) (*high confidence, very likely*).

Description of evidence base

Several sources were available to verify the extent of intertidal wetland and subtidal habitats in North America for Key Finding 1. First, the U.S Fish and Wildlife Service National Wetlands Inventory (USFWS NWI 2017) is a conservative but definitive source due to inclusion of tidal modifiers to clarify hydrology. Second, a synthesis of Mexican, Canadian, and U.S. saline coastal habitats was provided by the Commission for Environmental Cooperation (CEC 2016). For carbon density in intertidal wetland environments, a synthesis of datasets from tidal wetland habitats reviewed (Chmura et al., 2003; Ouyang and Lee 2014; Holmquist et al., 2018a) found a very narrow distribution measured in kilograms (kg; 27.0 ± 13.0 kg C per m^3) in wetland carbon stocks across North American tidal wetlands, regardless of salinity or vegetation type, as did a national dataset review (28.0 ± 7.8; Nahlik and Fennessy 2016). A global synthesis (Sanderman et al., 2018) provided data to synthesize a new estimate for Mexico's mangroves (31.8 ± 1.3 kg C per m^3). For carbon stocks in seagrass environments, synthetic data from literature reviews reporting bulk density and organic carbon along 1-m profiles were used for coast-specific estimates: 2.0 ± 1.3 for the Atlantic Coast, 3.1 ± 2.4 for the Gulf of Mexico coast, 1.4 ± 1.2 for the Pacific Coast, and 2.0 for boreal and Arctic regions. For carbon density in estuarine open-water sediments, coastal regions played no clear role and geomorphic settings were not available (Smith et al., 2015), so a mean of 1.0 kg per m^3 was chosen, using a literature-based average for total organic carbon (TOC) content (0.4% organic carbon; range 0.17% to 2%; Premuzic et al., 1982; Kennedy et al., 2010) coupled with a literature average of percentage of dry bulk densities (2.6 g C per cm^3; Muller and Suess 1979).

Major uncertainties

Uncertainties vary for each subhabitat, and these data likely represent an underestimate of total stocks, which may be many meters deep. For tidal wetland soils to 1 m in depth, the primary uncertainty is in underestimates of mapped boundaries, with, for example, no accounting of freshwater tidal systems in either Mexico or Canada, and likely undercounting of freshwater tidal wetlands in the United States. For seagrass, the spatial data are conservative estimates of located and documented habitat, although seagrass populations can shift boundaries rapidly and potentially there are far more currently unmapped seagrass beds in North America. For estuarine spatial data, the boundaries are constrained by bathymetry maps, which generally are more uncertain in higher latitudes. In contrast, carbon densities have narrow ranges in tidal wetland and estuarine soils but a skewed representation in seagrass soils, a difference which may be due to limited sampling in northern latitudes.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is theoretical and empirical convergence on tidal marsh carbon densities but a likely bias to underrepresenting tidal freshwater habitats. Further, seagrass carbon densities show a wider range and an apparent latitudinal gradient of decreasing carbon density from tropical to temperate

environments. Geomorphic variability (e.g., shallow waters versus fjords) in estuarine sediments may reduce uncertainty in stock assessments, but map layers are not available for North America.

Estimated likelihood of impact or consequence, including short description of basis of estimate

The likely impact of information is high because it has not been synthesized previously at the continental scale.

Summary sentence or paragraph that integrates the above information

For Key Finding 1, although sediment carbon densities in tidal wetlands are high with a narrow range and carbon densities in subtidal habitats are substantially lower with a wider range, there are still underrepresented samples from high-latitude regions, especially tidal forested wetlands and subtidal seagrasses. Further, the data reported thus far are limited to documented tidal habitats, although there is an appreciation that large areas are likely missing for freshwater tidal marsh and for seagrass extent.

KEY FINDING 2

Soil carbon accumulation rate (i.e., sediment burial) in North American tidal wetlands is currently 9 ± 5 Tg C per year (*high confidence, likely*), and estuarine carbon burial is 5 ± 3 Tg C per year (*low confidence, likely*).

Description of evidence base

Carbon burial, which accounts for all carbon accumulated in coastal sediments over an annual time period, has been documented for Key Finding 2, with geological approaches in multiple studies. Accumulation of carbon stock over a period of time using a marker horizon is relevant to specific periods of time by the method used (e.g., recent years, marker horizons, and radioisotope tracers of different decay rates). The data reported here refer to isotopes of cesium (^{137}Cs) and lead (^{210}Pb) dates alone, thus representing long-term average annual accretion rates for the past 50 years (since 1963). Rates of burial (Ouyang and Lee 2014; n = 125 samples) provide a range for comparison with other reviews that do account for mangrove subhabitats. No significant differences in carbon burial are detected for habitat types by salinity or vegetation type when comparing with Chmura et al. (2003) or with Breithaupt et al. (2014). Estuarine carbon burial is estimated for CONUS using the model of Herrmann et al. (2015) and scaled to all of North America using estimates of estuarine area.

Major uncertainties

Carbon burial rate is a bulk measure of multiple processes, both old and new carbon inputs as well as both autochthonous and allochthonous sources. As such, carbon burial through those processes has varied drivers, with different dominating processes across the landscape. Overestimation is possible when accretion of mineral sediment brings lower carbon densities than equilibrium conditions. Underestimates are possible when accretion is reported at historic rates and not adjusted for current rates of sea level rise. Mapped areas are a likely underestimate because they do not include freshwater tidal marshes in Canada or Alaska. Further, high uncertainties are associated with wide ranges of rates through different dating approaches. Estuarine carbon burial rate uncertainties stem from errors in the model of Herrmann et al. (2015) and, more

importantly, the scaling of CONUS results to all of North America. Particularly problematic is the lack of rigorous mapping of estuarine extent outside of CONUS.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Because mapping limitations and 50-year averages of tidal wetland carbon accumulation are inferred rather than being the current rates under accelerated sea level rise, these estimates likely are lower than the actual rates of burial. Thus, while these data represent measured rates, this analysis relies on a fairly small range of locations and a small subset of available published data. Estuarine burial rates are not confident because Canada and Mexico have limited data applicable to the modeling strategy of Herrmann et al. (2015).

Estimated likelihood of impact or consequence, including short description of basis of estimate

The likely impact of the information on tidal wetland and estuarine burial is high, as it has not yet been synthesized at the continental scale.

Summary sentence or paragraph that integrates the above information

For Key Finding 2, burial of carbon sourced from within wetlands and from terrestrial sources is similar among regions and wetland types, driven primarily by accretion rates, which are tied to geomorphic feedbacks with sea level rise. Burial of carbon in estuaries is linked most closely to residence time and total nitrogen input.

KEY FINDING 3

The lateral flux of carbon from tidal wetlands to estuaries is 16 ± 10 Tg C per year for North America (*low confidence, likely*).

Description of evidence base

In Key Finding 3, 16 studies were conducted to quantify the lateral flux of organic carbon (12 studies) and inorganic carbon (4 studies) from tidal wetlands to estuaries at individual locations. The organic carbon flux studies are summarized in Herrmann et al. (2015) and the inorganic carbon flux studies are summarized in Najjar et al. (2018). These studies were scaled to all of North America using estimates of tidal wetland area.

Major uncertainties

The major uncertainty in this Key Finding is the limited spatial and temporal extents of the 16 individual flux measurements. Tidal wetlands are highly heterogeneous and vary in their processing of carbon on a wide variety of timescales. Hence, tidal wetlands are likely to have been undersampled in terms of lateral exchanges. However, tidal wetlands consistently export carbon and the range of estimates is less than an order of magnitude.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

The low confidence is due to the limited number of measurements and time periods. There is appreciation, however, that at a continental scale, there is a strong likelihood that tidal wetlands export carbon to estuaries, although the magnitude of the flux is highly uncertain.

Estimated likelihood of impact or consequence, including short description of basis of estimate

This flux represents 60% (best estimate) of the net uptake of atmospheric carbon by tidal wetlands. Per knowledge gained, this is the first such estimate for North America.

Summary sentence or paragraph that integrates the above information

For Key Finding 3, there is enough information to make a first-order estimate of the flux of carbon from tidal wetlands to estuaries for North America as a whole, and there is high confidence in the order of magnitude of the flux. The high heterogeneity of tidal wetland systems and limited field data prevent a more accurate estimate of the flux.

KEY FINDING 4

In North America, tidal wetlands remove 27 ± 13 Tg C per year from the atmosphere, estuaries outgas 10 ± 10 Tg C per year to the atmosphere, and the net uptake by the combined wetland-estuary system is 17 ± 16 Tg C per year (*low confidence, likely*).

Description of evidence base

The uptake of atmospheric carbon dioxide (CO_2) by tidal wetlands is assessed for Key Finding 4 by net ecosystem exchange (NEE) estimates from eddy covariance measurements. It is similar to an alternative estimate of uptake that assumes uptake as the sum of burial (8 Tg C) and lateral export (16 Tg C). Burial and lateral exports are discussed in the supporting evidence for Key Findings 2 and 3. Estuarine outgassing is based on studies of individual estuary summaries (Chen et al., 2013) and estuarine areas (Laruelle et al., 2013). The flux of the combined system is a simple sum of the fluxes from tidal wetlands and estuaries and compounded error.

Major uncertainties

The major uncertainties in this Key Finding are the limited spatial and temporal extents of tidal wetland atmospheric flux measurements, burial, lateral flux, and estuarine outgassing measurements. Estuarine outgassing uncertainties also stem from the low spatial resolution of the datasets used to estimate areas.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is low confidence on this calculation at the scale of North America. The low confidence is due to the residual between competing fluxes; on the one hand, there is strong likelihood that tidal wetlands take up CO_2 from the atmosphere and estuaries outgas CO_2 to the atmosphere and, on the other hand, that there is large uncertainty in the magnitude of each, assessments which stem from the high spatial and temporal variability of these systems and the limited field data. The fate of carbon released from tidal wetland degradation remains unknown.

Estimated likelihood of impact or consequence, including short description of basis of estimate

These are not major fluxes in the carbon budget of North America, but they are regionally important. Accounting for current knowledge, such estimates are the first for North America.

Summary sentence or paragraph that integrates the above information

For Key Finding 4, there is enough information to make first-order estimates of the exchange of atmospheric CO_2 with tidal wetlands and estuaries for North America as a whole. The high heterogeneity of these systems and limited field data prevent a more accurate estimate of the flux.

KEY FINDING 5

Research and modeling needs are greatest for understanding responses to accelerated sea level rise; mapping tidal wetland and estuarine extent; and quantifying carbon dioxide and methane exchange with the atmosphere, especially in large, undersampled, and rapidly changing regions (*high confidence, likely*).

Description of evidence base

Tidal wetland and estuarine area are first-order drivers of the spatially integrated flux (e.g., in units of Tg C per year) of all carbon fluxes in these ecosystems. The lack of an accurate quantification of tidal wetland and estuarine area, particularly in Canada and Mexico, is thus a major gap in understanding the role of tidal wetlands and estuaries in the carbon cycling of North America. Carbon cycle research is largely motivated by the impact of greenhouse gases on climate and how climate change affects fluxes of these gases to the atmosphere from terrestrial and aquatic systems. However, the database of tidal wetland and estuarine CO_2 and CH_4 exchanges with the atmosphere is severely limited. In particular, direct estimates of these fluxes are rare. Furthermore, some of the most poorly sampled regions are those that are changing the most rapidly (e.g., the Arctic).

Major uncertainties

There are few uncertainties in Key Finding 5 because there is a clear lack of data on extent and atmospheric exchange.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Confidence is high in Key Finding 5 because systematic studies (with error estimates) of tidal wetlands and estuaries are extremely limited. Very few direct estimates of exchanges of atmospheric CO_2 and CH_4 with tidal wetlands and estuaries exist. While research needs are present in other aspects of the tidal wetland and estuarine carbon cycling, these needs are unlikely to be more pressing than the needs for quantifying area and gas exchange with the atmosphere.

Estimated likelihood of impact or consequence, including short description of basis of estimate

Key Finding 5 is not an estimate but a recommendation. It could impact future research on tidal wetland and estuarine carbon cycling in North America.

Summary sentence or paragraph that integrates the above information

Key Finding 5 synthesizes the existing research on tidal wetland and estuarine carbon cycling in North America, providing a future direction for research in this area.

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Appendix 15A
Supplemental Data Tables

Table 15A.1. Summary of North American Carbon Dioxide Exchange Between Tidal Wetlands and the Atmosphere (Net Ecosystem Exchange[a]) from Continuous Measurements[b]

System Name and Type	Location	EC/SC	Year	NEE (g C per m² per year)	Source
Pacific Coast					
Rush Ranch, Suisun Bay, brackish marsh	California	EC	2014–2015 2015–2016 2016–2017	14 –190 –222	Bergamaschi and Windham-Myers (2018)
Atlantic Coast					
Plum Island, salt marsh	Massachusetts	EC	2012 2013 2014	–255.6 –336.0 –279.6	Forbrich and Giblin (2015)
Waquoit Bay, salt marsh	Massachusetts	SC	2015	–160.0	Moseman-Valtierra et al. (2016)
Hudson-Raritan Estuary, restored salt marsh	New Jersey	EC	2009 2011 2012	984[c] –64.8 –309.6	Schäfer et al. (2014)
Hudson-Raritan Estuary, restored salt marsh	New Jersey	EC	2011–2012	–213.6	Artigas et al. (2015)
Delaware Bay, tidal fresh marsh	New Jersey	SC	2007 2008	–256.8 61.2	Weston et al. (2014)
Delaware Bay, oligohaline marsh	New Jersey	SC	2007 2008	93.6 –45.6	Weston et al. (2014)
Delaware Bay, mesohaline marsh	New Jersey	SC	2007 2008	–115.2 –171.6	Weston et al. (2014)
Fowling Point, salt marsh	Virginia	SC	2007	–129.6	Kathilankal et al. (2008)

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Table 15A.1. Summary of North American Carbon Dioxide Exchange Between Tidal Wetlands and the Atmosphere (Net Ecosystem Exchange[a]) from Continuous Measurements[b]

System Name and Type	Location	EC/SC	Year	NEE (g C per m² per year)	Source
Springfield Creek, tidal fresh marsh	South Carolina	SC	2009	–295.2	Neubauer et al. (2013)
Gulf of Mexico					
Pointe-aux-Chenes, brackish marsh	Louisiana	EC	2011	–337.2	Holm et al. (2016)
Salvador, tidal fresh marsh	Louisiana	EC	2011	170.4	Holm et al. (2016)
Florida Bay, mangrove	Florida	EC	2004	–1172.4	Barr et al. (2010); Barr et al. (2012)
			2005	–1176	
			2007	–823.2	
			2008	–806.4	
			2009	–926.4	
Mobile Bay, tidal fresh marsh	Alabama	SC	2011	893.4	Wilson et al. (2015)
Mobile Bay, brackish marsh	Alabama	SC	2011	517.8	Wilson et al. (2015)
Mobile Bay, salt marsh	Alabama	SC	2011	410.2	Wilson et al. (2015)

Notes

a) NEE, Net ecosystem exchange; g C, grams of carbon.

b) Continuous measurements: eddy covariance (EC) or static chamber (SC). Positive values = atmospheric carbon dioxide (CO_2) source. Negative values = atmospheric CO_2 sink. Annual estimate (mean) provided.

c) Mudflat habitat (very little data available in literature).

Table 15A.2. Tidal Wetland Methane Flux by Discrete Static Chamber Data or Continuous Eddy Covariance[a] Data

Site Name	Location	Year	EC/SC	Salinity (PSU[b])	CH_4 Flux (g C per m^2 per year)[c]	Reference
Atlantic Coast						
Upland edge	New Brunswick	1993	SC	**23.5**	1.0	Magenheimer et al. (1996)
High marsh				**31.6**	0.2	
Middle marsh				**33.7**	0.2	
Low marsh				**35.1**	0.2	
Dipper Harbour	New Brunswick	2011–2012	SC	**23.7**	0.1	Chmura et al. (2016)
Kouchibouguac				**13.7**	0.0	
Creek Bank	Virginia	1981–1983	SC	18.7	0.9	Bartlett et al. (1985)
High marsh				22.6	0.3	
Short *Spartina*				26.3	1.0	
Site 1	Virginia	1983–1984	SC	**5.1**	13.7	Bartlett et al. (1987)
Site 2		1983–1984	SC	**12.8**	16.8	
Site 3		1983–1984	SC	**16.6**	4.2	
Sweet Hall	Virginia	1996–1997	SC	0.25	72.0	Neubauer et al. (2000)
C_3 Ambient CO_2	Maryland	1998–1999	SC	6.8	3.5	Marsh et al. (2005)
C_4 Ambient CO_2	Maryland	1998–1999	SC	6.8	2.5	
Tidal freshwater marsh	Delaware	2007	SC	0.25	20.0	Weston et al. (2014)
		2008		0.25	24.0	
Oligohaline marsh		2007		2.5	123.0	
Mesohaline marsh		2008		2.5	87.0	
		2007		10	–5.0	
		2008		10	–2.0	
Wildlife	Maryland	2008	SC	11.6	23.0	Poffenbarger et al. (2011)
Barbados	Maryland	2008	SC	12.9	24.0	

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Table 15A.2. Tidal Wetland Methane Flux by Discrete Static Chamber Data or Continuous Eddy Covariance[a] Data

Site Name	Location	Year	EC/SC	Salinity (PSU[b])	CH_4 Flux (g C per m² per year)[c]	Reference
Vegetated low marsh	New Jersey	2012	SC	**5**	4.3	Reid et al., (2013)
Mud flat		2012	SC	**5**	3.8	
Fox Creek Marsh	Maryland	2013–2014	SC	**10**	79.1	Mueller et al. (2016)
				10	3.9	
				10	0.8	
Kirkpatrick Marsh				**10**	10.1	
				10	3.4	
				10	2.3	
GI Near Bank	North Carolina	1990–1991	SC	0.25	6.2	Kelley et al. (1995)
GI Far Bank				0.25	4.3	
UF Near Bank				0.25	3.8	
UF Far Bank				0.25	2.6	
Lower site	North Carolina	1994–1995	SC	0.25	1.0	Megonigal and Schlesinger (2002)
Upper site				0.25	1.4	
Upper	Georgia	2006–2007	SC	**0.2**	0.8	Krauss and Whitbeck (2011)
Middle	Georgia	2006–2007	SC	**1.3**	1.0	
Lower	Georgia	2006–2007	SC	**4.7**	1.0	
Georgia Coastal Ecosystems LTER[d]	Georgia	2008–2009	SC	1	69.8	Segarra et al. (2013)
Brookgreen Gardens	South Carolina	2009	SC	**0.05**	42.0	Neubauer et al. (2013)
Gulf of Mexico						
Fresh	Louisiana	1980–1981	SC	0.4	160.0	DeLaune et al. (1983)
Brackish				1.8	73.0	
Salt Marsh				18.1	4.3	

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Table 15A.2. Tidal Wetland Methane Flux by Discrete Static Chamber Data or Continuous Eddy Covariance[a] Data

Site Name	Location	Year	EC/SC	Salinity (PSU[b])	CH_4 Flux (g C per m^2 per year)[c]	Reference
Brackish marsh	Louisiana	2012	EC	9.15	10.4	Holm et al. (2016)
Freshwater marsh		2012	EC	0.23	47.3	
		2013	EC	0.23	46.2	
Brackish marsh	Louisiana	2012–2013	EC	9.15	11.1	Krauss et al. (2016)
			SC	9.15	49.6	
Freshwater marsh			EC	0.23	47.1	
			SC	0.23	91.9	
Week's Bay	Alabama	2012–2013	SC	**2.3**	7.9	Wilson et al. (2015)
Dog River				**4.7**	3.9	
Dauphin Island				**20.7**	4.3	

Notes

a) CH_4, methane; CO_2, carbon dioxide; SC, static chamber; EC, eddy covariance; g C, grams of carbon.

b) Salinity values in bold indicate porewater salinity; otherwise, channel salinity is reported (where PSU = practical salinity units). When salinity was not reported for tidal freshwater wetlands, a value of 0.25 was assigned, which represents the midpoint of their salinity range (0 to 0.5) by definition.

c) Positive values = atmospheric CH_4 source. Negative values = atmospheric CH_4 sink. Annual estimate provided.

d) LTER, Long-term ecological research.

Table 15A.3. Estuarine Carbon Dioxide Outgassing (Emissions) for the U.S. Pacific Coast, Atlantic Coast,[a] and Gulf of Mexico Regions[b,c]

System Name	Location	Subregion	Source	CO_2 Flux (g C per m^2 per year)[c]	CO_2 Flux Integral (Tg C per year)
Pacific Coast: Northwest					
Columbia River	Oregon, WA	Northwest	Evans et al. (2012)	12	NA[d]
Atlantic Coast: Gulf of Maine (GOM) Subregion[a]					
Bellamy Estuary	Massachusetts, USA	GOM	Hunt et al. (2011)	55	
Cocheco Estuary	Massachusetts, USA	GOM	Hunt et al. (2011)	44	
Great Bay	Massachusetts, USA	GOM	Hunt et al. (2011)	43	
Kennebec Estuary	Massachusetts, USA	GOM	Hunt et al. (2014)	30	
Little Bay	Massachusetts, USA	GOM	Hunt et al. (2011)	48	
Oyster Estuary	Massachusetts, USA	GOM	Hunt et al. (2011)	48	
Parker River	Massachusetts, USA	GOM	Raymond and Hopkinson (2003)	13	
			Mean	**40**	**0.22**
			Standard error	**5**	**0.03**
Atlantic Coast: Mid-Atlantic Bight (MAB) Subregion[a]					
Delaware River	Delaware/ New Jersey, USA	MAB	Joesoef et al. (2015)	29	
York River	Virginia, USA	MAB	Raymond et al. (2000)	67	
			Mean	**48**	**1.0**
			Standard error	**19**	**0.4**
Atlantic Coast: South Atlantic Bight (SAB) Subregion[a]					
Altamaha Sound	Georgia, USA	SAB	Jiang et al. (2008)	322	
Doboy Sound	Georgia, USA	SAB	Jiang et al. (2008)	143	
Duplin River	Georgia, USA	SAB	Wang and Cai (2004)	256	
Neuse River	N. Carolina, USA	SAB	Crosswell et al. (2012); Crosswell et al. (2014)	–68	
Pamlico Sound	N. Carolina, USA	SAB	Crosswell et al. (2014)	–180	
Sapelo Sound	Georgia, USA	SAB	Jiang et al. (2008)	126	

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Table 15A.3. Estuarine Carbon Dioxide Outgassing (Emissions) for the U.S. Pacific Coast, Atlantic Coast,[a] and Gulf of Mexico Regions[b,c]

System Name	Location	Subregion	Source	CO_2 Flux (g C per m² per year)[c]	CO_2 Flux Integral (Tg C per year)
Satilla River	Georgia, USA	SAB	Cai and Wang (1998)	510	
			Mean	**158**	**1.9**
			Standard error	**88**	**1.1**
Atlantic Coast Totals					
			Mean	**82**	**3.1**
			Standard error	**30**	**1.1**
Gulf of Mexico (GMx)					
Atchafalaya River	Louisiana, USA	GMx	Huang et al. (2015)	504	
Florida Bay	Florida, USA	GMx	Zhang and Fischer (2014)	47	
Mission-Aransas Estuary	Texas, USA	GMx	Yao and Hu (2017)	149	
Mississippi River	Louisiana, USA	GMx	Huang et al. (2015)	444	
Shark River	Florida, USA	GMx	Kone and Borges (2008)	192	
Terrebonne Bay	Louisiana, USA	GMx	Huang et al. (2015)	–4	
			Mean	**222**	**6.8**
			Standard error	**85**	**2.6**
Atlantic Coast and Gulf of Mexico Totals					
			Mean		**9.9**
			Standard error		**2.8**

Notes

a) The Atlantic Coast is subdivided into three subregions: Gulf of Maine, Mid-Atlantic Bight, and South Atlantic Bight.

b) Positive values = atmospheric CO_2 source; negative values = atmospheric CO_2 sink. A spatially representative annual CO_2 flux integral is not calculated for the Pacific Coast due to the presence of only one study and limited seasonal sampling.

c) CO_2, carbon dioxide; g C, grams of carbon; Tg C, teragrams of carbon.

d) NA (or blank): Not assessed.

16 Coastal Ocean and Continental Shelves

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KEY FINDINGS

1. Observing networks and high-resolution models are now available to construct coastal carbon budgets. Efforts have focused primarily on quantifying the net air-sea exchange of carbon dioxide (CO_2), but some studies have estimated other key fluxes, such as the exchange between shelves and the open ocean.

2. Available estimates of air-sea carbon fluxes, based on more than a decade of observations, indicate that the North American margins act as a net sink for atmospheric CO_2. This net uptake is driven primarily by fluxes in the high-latitude regions. The estimated magnitude of the net flux is 160 ± 80 teragrams of carbon per year (*medium confidence*) for the North American Exclusive Economic Zone, a number that is not well constrained.

3. The increasing concentration of CO_2 in coastal and open-ocean waters leads to ocean acidification. Corrosive conditions in the subsurface occur regularly in Arctic coastal waters, which are naturally prone to low pH, and North Pacific coastal waters, where upwelling of deep, carbon-rich waters has intensified and, in combination with the uptake of anthropogenic carbon, leads to low seawater pH and aragonite saturation states in spring, summer, and early fall (*very high confidence, very likely*).

4. Expanded monitoring, more complete syntheses of available observations, and extension of existing model capabilities are required to provide more reliable coastal carbon budgets, projections of future states of the coastal ocean, and quantification of anthropogenic carbon contributions.

Note: Confidence levels are provided as appropriate for quantitative, but not qualitative, Key Findings and statements.

16.1 Introduction

Along ocean margins, the atmospheric, terrestrial, sedimentary, and deep-ocean carbon reservoirs meet, resulting in quantitatively significant carbon exchanges. Anthropogenic activities lead to secular trends in these exchanges. The drivers underlying these trends include rising atmospheric carbon dioxide (CO_2) levels, climate-driven changes in atmospheric forcing (e.g., winds and heat fluxes) and the hydrological cycle (e.g., freshwater input from rivers), and changes in riverine and atmospheric nutrient inputs from agricultural activities and fossil fuel burning. The collective impact of these factors on carbon processing and exchanges along ocean margins is complex and difficult to quantify (Regnier et al., 2013).

This chapter focuses on two particularly pressing issues within the much broader topic of carbon cycling along ocean margins: 1) the uptake of atmospheric CO_2 and subsequent export to the deep ocean and 2) patterns and drivers of coastal ocean acidification. The first is relevant to overall quantification of the ocean's uptake of CO_2. The second is directly relevant to coastal ecosystem health, fisheries, and aquaculture.

Two different terms will be used here when referring to ocean margins: 1) the coastal ocean, defined in this report as nonestuarine waters within 200 nautical miles (370 km) of the coast, and 2) continental shelves, which refer to the submerged margins of the continental plates, operationally defined here as regions with water depths shallower than 200 m (indicated in gray in Figure 16.1, p. 651). Although the two definitions overlap, there are important reasons for considering both. Along passive margins with broad shelves like the North American Atlantic Coast, the continental shelf is the relevant spatial unit for discussing carbon fluxes. Along active margins with narrow shelves, such as the North American Pacific Coast, a larger region than just the shelf needs to be considered to meaningfully discuss coastal carbon dynamics. The 370-km limit chosen here to define the coastal ocean was recommended by Hales et al. (2008) and corresponds to the Exclusive

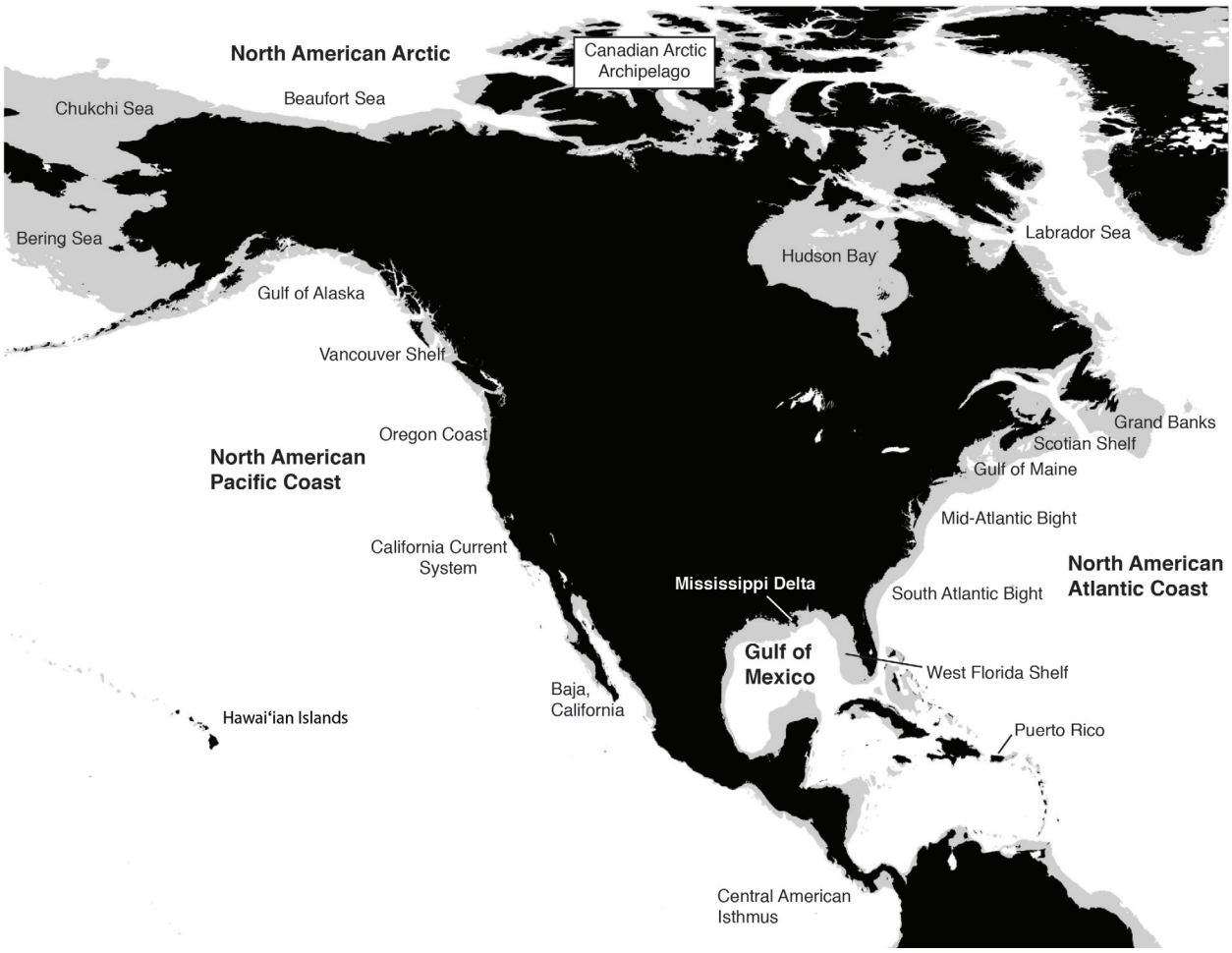

Figure 16.1. North American Shelf Seas. These seas (in gray) are defined as waters with bottom depths less than 200 m.

Economic Zone (EEZ, the region where a nation can claim exclusive rights for fishing, drilling, and other economic activities). Worth noting here is that ocean CO_2 uptake or loss is not credited to any nation under Intergovernmental Panel on Climate Change (IPCC) CO_2 accounting; instead, ocean uptake is viewed as an internationally shared public commons.

This chapter builds on and extends several previous synthesis and planning activities, including a report by the North American Continental Margins Working Group (Hales et al., 2008), the *First State of the Carbon Cycle Report* (SOCCR1; CCSP 2007; Chavez et al., 2007), and activities within the North American coastal interim synthesis (Benway et al., 2016; Alin et al., 2012; Najjar et al., 2012; Mathis and Bates 2010; Robbins et al., 2009). SOCCR1 (Chavez et al., 2007) concluded that carbon fluxes for North American ocean margins were not well quantified because of insufficient observations and the complexity and highly localized spatial variability of coastal carbon dynamics. The report was inconclusive as to whether North American coastal waters act as an overall source or sink of atmospheric CO_2.

The objective here is to provide a review and synthesis of recent findings with respect to coastal carbon uptake and ocean acidification for the margins of North America. Summarized first are the key

variables and fluxes relevant to carbon budgets for coastal waters, followed by descriptions of 1) the mechanisms by which carbon can be removed from the atmospheric reservoir and 2) the means for quantifying the resulting carbon removal (see Section 16.2, this page). Next presented is available research relevant to carbon budgets for North American coastal waters by region, along with an assessment of whether enough information is available to derive robust estimates of carbon export to the open ocean (see Section 16.3, p. 655). Climate-driven trends in coastal carbon fluxes and coastal ocean acidification are then discussed (see Section 16.4, p. 669), followed by conclusions (see Section 16.5, p. 673).

16.2 Current Understanding of Carbon Fluxes and Stocks

Carbon is present in various inorganic and organic forms in coastal waters (see Figure 16.2, p. 653). Dissolved inorganic species include aqueous CO_2 (a combination of dissolved CO_2 and carbonic acid), bicarbonate and carbonate ions, and methane (CH_4); the first three carbon species are collectively referred to as dissolved inorganic carbon or DIC. The major particulate inorganic species is calcium carbonate ($CaCO_3$), also referred to as particulate inorganic carbon (PIC). Carbon is also present in various dissolved and particulate organic forms (DOC and POC). In shelf waters, the reduced carbon pool or total organic carbon pool (TOC) represents roughly 2% to 5% of the total carbon stock (Liu et al., 2010), and DOC constitutes more than 90% to 95% of this TOC (Vlahos et al., 2002).

Carbon is constantly transferred among these different pools and exchanged across the interfaces that demarcate coastal waters: the land-ocean interface, the air-sea interface, and the interface between coastal and open-ocean waters (see Figure 16.2, p. 653). The internal carbon transformations within coastal regions include photosynthetic primary production, respiration, transfers between lower and higher trophic levels of the food web, exchanges between sediment and overlying water, biogeochemical processes in the sediment, and the formation and dissolution of $CaCO_3$. Major internal transformations are the conversion of DIC into organic carbon (POC and DOC), through primary production, and respiration throughout the water column, returning most of the organic carbon into inorganic forms (primarily DIC). Some POC settles out of the water column and becomes incorporated into the sediments where most of this material is respired through a range of different redox processes that produce DIC and, under certain circumstances, CH_4 (i.e., in the relative absence of electron acceptors other than CO_2). Both DIC and CH_4 are released back into the overlying water. POC that is not respired (referred to as refractory POC) can be buried in sediments and stored for a very long time. Some organisms form internal or external body structures of $CaCO_3$, which either dissolve or become incorporated into the sediments and are buried. This discussion will refer to long-term storage of buried POC and PIC in coastal sediments as permanent burial.

A major carbon exchange process along the ocean margin is the flux of CO_2 across the air-sea interface. The annual cycle of this flux is driven by 1) seawater warming and cooling, which affects CO_2 solubility; 2) the under- or oversaturation of CO_2 resulting from primary production, respiration, and $CaCO_3$ precipitation and dissolution; 3) the transport of DIC to and from the ocean surface (e.g., upwelling and convection); and 4) factors that influence the resistance to gas exchange across the air-sea interface (e.g., winds, sea ice extent, and surface films). The annual cycles of primary production, respiration, and air-sea CO_2 flux tend to be of larger magnitude and more variable in coastal waters than in the open ocean (Bauer et al., 2013; Liu et al., 2010; Muller-Karger et al., 2005; Thunell et al., 2007; Xue et al., 2016) and more pronounced in high latitudes. Other important exchange fluxes are organic and inorganic carbon inputs from land via rivers and estuaries (see Ch. 15: Tidal Wetlands and Estuaries, p. 596), from tidal wetlands, and exchanges between the coastal and open oceans across the continental shelf break or the operationally defined open-ocean boundary of the coastal ocean. Net removal of carbon from direct interaction with the atmospheric

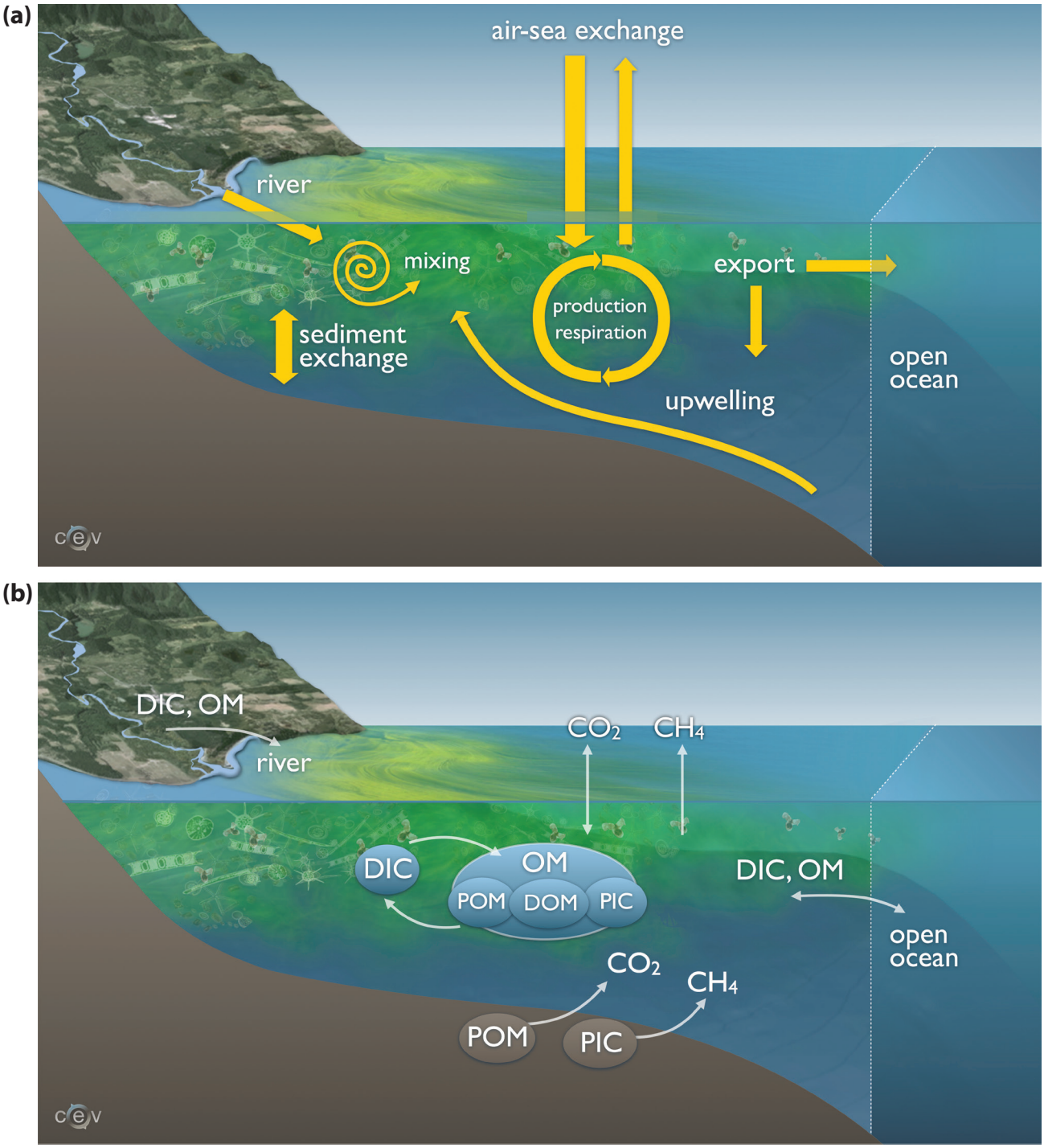

Figure 16.2. Major Coastal Carbon Pools and Fluxes. (a) Carbon in various forms (e.g., CO_2, carbon dioxide; CH_4, methane) is transferred among different pools and exchanged across interfaces between land, air, and ocean in coastal regions. **(b)** Carbon forms include dissolved inorganic carbon (DIC), organic matter (OM), particulate organic matter (POM), dissolved organic matter (DOM), and particulate inorganic matter (PIC). [Figure sources: Simone Alin, National Oceanic and Atmospheric Administration; Hunter Hadaway, University of Washington Center for Environmental Visualization; and Katja Fennel, Dalhousie University.]

reservoir can occur by export to the deep ocean or by permanent burial in coastal sediments.

Although continental shelves make up only 7% to 10% of the global ocean surface area, they are estimated to contribute up to 30% of primary production, 30% to 50% of inorganic carbon burial, and 80% of organic carbon burial (Dunne et al., 2007; Gattuso et al., 1998). As such, continental shelves have been argued to contribute disproportionately to the oceanic uptake of CO_2 (Cai 2011; Liu et al., 2010; Muller-Karger et al., 2005).

Carbon export, referring to the flux of organic and inorganic carbon from coastal waters to the deep ocean, can occur through the so-called "Continental Shelf Pump"—a term coined by Tsunogai et al. (1999) after they observed a large uptake of atmospheric CO_2 in the East China Sea. There are two distinct mechanisms underlying the Continental Shelf Pump (Fennel 2010). The first is physical in nature and thought to operate in mid- and high-latitude systems. In winter, shelf water is cooled more strongly than surface water in the adjacent open ocean because the former is not subject to deep convection. The colder shelf water is denser and experiences a larger influx of atmospheric CO_2; both density and the solubility of CO_2 increase with decreasing temperature. If this dense and carbon-rich water is transported off the shelf, it will sink due to its higher density, and the associated carbon will be exported to the deep ocean. The second mechanism relies on biological processes that concentrate carbon below the seasonal pycnocline (i.e., photosynthetic production of organic carbon and subsequent sinking). If the carbon-rich water below the seasonal pycnocline is moved off the shelf horizontally, carbon potentially could be exported if this water is transported or mixed below the seasonal thermocline. The depth to which the shelf-derived carbon can be exported will be different for POC, which will sink, and DOC and DIC, which primarily would be advected laterally. Both mechanisms for carbon export critically depend on physical transport of carbon-rich water off the shelf.

Carbon export flux from coastal waters to the deep ocean cannot be quantified easily or accurately through direct observation. Thus, the only available estimates of such export are indirect, using mass balances of POC and dissolved oxygen (Hales et al., 2006), mass balances of DOC (Barrón and Duarte 2015; Vlahos et al., 2002), mass balances of TOC and DIC (Najjar et al., 2018), and model estimates (Izett and Fennel 2018a, 2018b; Bourgeois et al., 2016; Fennel and Wilkin 2009; Fiechter et al., 2014; Mannino et al., 2016; Turi et al., 2014; Xue et al., 2013). If the total carbon inventory in a coastal system can be considered constant over a sufficiently long timescale (i.e., on the order of years), inferring carbon export is possible from using the sum of all other exchange fluxes across the system's interfaces over that same period. Export to the open ocean must balance the influx of carbon from land and wetlands, its net exchange across the air-sea interface, lateral exchange caused by advection, and any removal through permanent sediment burial. The accuracy of the inferred export flux directly depends on the accuracy of the other flux estimates and of the assumption of a constant carbon inventory. Quantifying internal transformation processes (e.g., respiration and primary and secondary production) does not directly enter this budgeting approach but can elucidate the processes that drive fluxes across interfaces.

Current estimates of carbon fluxes across coastal interfaces come with significant uncertainties (Regnier et al., 2013; Birdsey et al., 2009). These uncertainties are caused by a combination of 1) small-scale temporal and spatial variability, which is undersampled by currently available means of direct observation, and 2) regional heterogeneity, which makes scaling up observations from one region to larger areas difficult. Contributing to variability in regional carbon budgets and export are geographical differences arising from variations in shelf width, the presence or absence of large rivers, seasonal ice cover, and latitude through its modulation of annual temperature and productivity cycles and of hydrography due to the rotation of the Earth (Sharples et al., 2017). Section 16.3, p. 655, describes the regional characteristics of North American

coastal waters and how these characteristics influence carbon dynamics. Available estimates of carbon fluxes are compiled in an attempt to estimate export.

The motivation for quantifying permanent burial of carbon and export of carbon from coastal waters to the deep ocean is that both processes remove CO_2 from the atmospheric reservoir. A more relevant but harder to obtain quantity in this context is the burial or export of anthropogenic carbon. The anthropogenic component of a given carbon flux is defined as the difference between its preindustrial and present-day fluxes. Thus, present-day carbon fluxes represent a superposition of the anthropogenic flux component and the natural background flux. Only total fluxes—the sum of anthropogenic and background fluxes—can be observed directly. Distinction between anthropogenic fluxes and the natural background is difficult to assess for coastal ocean fluxes and has to rely on process-based arguments and models (Regnier et al., 2013). Observation-based estimates of the global open ocean's anthropogenic uptake have been made by Sabine et al. (2004), Sabine and Tanhua (2010), and Carter et al. (2017). Bourgeois et al. (2016) were the first to estimate coastal anthropogenic carbon uptake in their global model. Their estimates are presented in some detail in Section 16.3.5, p. 665.

16.3 Coastal Carbon Fluxes Around North America

16.3.1 North American Atlantic Coast

The North American Atlantic Coast borders on a wide, geologically passive margin shelf that extends from the southern tip of Florida to the continental shelf of the Labrador Sea (see Figure 16.1, p. 651). The shelf is several hundreds of kilometers wide in the north (Labrador shelf and Grand Banks) but narrows progressively toward the south in the Middle Atlantic Bight (MAB), which is between Cape Cod and Cape Hatteras, and the South Atlantic Bight (SAB), which is south of Cape Hatteras. The SAB shelf width measures only several tens of kilometers. Two major semi-enclosed bodies of water are the Gulf of Maine (GOM) and Gulf of St. Lawrence. Important rivers and estuaries north of Cape Hatteras include the St. Lawrence River and Estuary, the Hudson River, Long Island Sound, Delaware Bay, and Chesapeake Bay. South of Cape Hatteras, the coastline is characterized by small rivers and marshes. The SAB is influenced by the Gulf Stream, which flows northeastward along the shelf edge before detaching at Cape Hatteras and meandering eastward into the open North Atlantic Ocean. North of Cape Hatteras, shelf circulation is influenced by the confluence of the southwestward-flowing fresh and cold shelf-break current (a limb of the Labrador Current) and the warm and salty Gulf Stream (Loder et al., 1998). Because shelf waters north of Cape Hatteras are sourced from the Labrador Sea, they are relatively cold, fresh, and carbon rich, while slope waters (those located between the shelf break and the northern wall of the Gulf Stream) are a mixture of Labrador Current and Gulf Stream water. Exchange between the shelf and open ocean across the shelf break is impeded by the presence of the Gulf Stream south of Cape Hatteras and by shelf-break jets and fronts north of Cape Hatteras.

Air-sea fluxes of CO_2 exhibit a large-scale latitudinal gradient along the North American Atlantic Coast and significant seasonal and interannual variability. The net flux on the Scotian Shelf remains controversial. Shadwick et al. (2010), combining *in situ* and satellite observations, reported a large source of CO_2 to the atmosphere of 8.3 ± 6.6 grams of carbon (g C) per m^2 per year. In contrast, Signorini et al. (2013) estimated a relatively large sink of atmospheric CO_2, 14 ± 3.2 g C per m^2 per year, when using *in situ* data alone and a much smaller uptake, 5.0 ± 4.3 g C per m^2 per year, from a combination of *in situ* and satellite observations. The open GOM is a weak net source of 4.6 ± 3.1 g C per m^2 per year according to Vandemark et al. (2011) but with significant interannual variability, while Signorini et al. (2013) estimate the region to be neutral. The shallow, tidally mixed GOM regions (i.e., Georges Bank and Nantucket Shoals) are thought to be sinks, however (see Table 16.1, p. 657; Signorini et al., 2013). The MAB and SAB are net sinks. Observation-based

estimates for the MAB include sinks of 13 ± 8.3 g C per m^2 per year (DeGrandpre et al., 2002) and 13 ± 3.2 g C per m^2 per year (Signorini et al., 2013). Estimates for the SAB include sinks of 5.8 ± 2.5 g C per m^2 per year (Jiang et al., 2008) and 8.2 ± 2.9 g C per m^2 per year (Signorini et al., 2013). The change from neutral or occasional net source in the Scotian Shelf and GOM regions to net sink in the MAB arises because the properties of shelf water are modified during its southwestward flow by air-sea exchange, inflows of riverine and estuarine waters (Salisbury et al., 2008b, 2009), and exchange with the open North Atlantic across the shelf break (Cai et al., 2010a; Wang et al., 2013). Outgassing of CO_2 on the Scotian Shelf is driven primarily by warming of cold, carbon-rich shelf water, which still carries a pronounced signature of its Labrador Sea origin. The GOM, which is deeper than the Scotian Shelf and the MAB and connected to the open North Atlantic through a relatively deep channel, is characterized by a mixture of cold, carbon-rich shelf waters and warmer, saltier slope waters. Shelf water in the MAB is sourced from the GOM and thus is a mixture of shelf and slope water.

Shelf water in the SAB is distinct from that in the MAB and has almost no trace of Labrador Current water; instead, its characteristics are similar to those of the Gulf Stream, but its carbon signature is modified by significant organic and inorganic carbon and alkalinity inputs from coastal marshes (Cai et al., 2003; Jiang et al., 2013; Wang and Cai 2004; Wang et al., 2005). Herrmann et al. (2015) estimated that 59% of the 3.4 teragrams of carbon (Tg C) per year of organic carbon exported from U.S. East Coast estuaries is from the SAB. The subsequent respiration of this organic matter and direct outgassing of marsh-derived carbon make the nearshore regions a significant CO_2 source almost year-round. Despite the carbon inputs from marshes, uptake of CO_2 on the mid- and outer shelf during the winter months is large enough to balance CO_2 outgassing in the other seasons and on the inner shelf, making the SAB overall a weak net sink (Jiang et al., 2008).

North of Cape Hatteras, CO_2 dynamics are characterized by strong seasonality with solubility-driven uptake by cooling in winter and biologically driven uptake in spring followed by outgassing in summer and fall due to warming and respiration of organic matter (DeGrandpre et al., 2002; Shadwick et al., 2010, 2011; Signorini et al., 2013; Vandemark et al., 2011; Wang et al., 2013). Hydrography and CO_2 dynamics on the Scotian Shelf are influenced by the significant freshwater input from the St. Lawrence River. Riverine inputs of carbon and nutrients are relatively small in the GOM but can cause local phytoplankton blooms, CO_2 drawdown, and low-pH conditions (Salisbury et al., 2008a, 2009). Riverine and estuarine inputs become more important in the MAB with discharges from the Chesapeake Bay and the Delaware, Hudson, and Connecticut rivers (Wang et al., 2013). South of Cape Hatteras, seasonal phytoplankton blooms do not occur regularly and biologically driven CO_2 uptake is less pronounced than that further north (Wang et al., 2013), although sporadic phytoplankton blooms do occur because of intrusions of high-nutrient subsurface Gulf Stream water (Wang et al., 2005, 2013). The influence of riverine inputs is small and localized in the SAB (Cai and Wang 1998; Wang and Cai 2004; Wang et al., 2005).

Regional biogeochemical models reproduce the large-scale patterns of air-sea CO_2 flux with oceanic uptake increasing from the SAB to the GOM (Cahill et al., 2016; Fennel et al., 2008; Previdi et al., 2009). These model studies elucidate the magnitude and sources of interannual variability as well as long-term trends in air-sea CO_2 fluxes. Previdi et al. (2009) investigated opposite phases of the North Atlantic Oscillation (NAO) and found that the simulated air-sea flux in the MAB and GOM was 25% lower in a high-NAO year compared with that in a low-NAO year. In the MAB, the decrease resulted primarily from changes in wind forcing, while in the GOM, changes in surface temperature and new production were more important. Cahill et al. (2016) investigated the impact of future, climate-driven warming and trends in atmospheric forcing (primarily wind) on air-sea CO_2 flux (without considering the

Table 16.1. Regional Estimates of Net Air-Sea Carbon Dioxide Exchange from Observations and Regional Models[a,b]

Region	Area (km^2)	Air-Sea Exchange		Observation-Based Estimate or Model	Reference
		g C per m^2 per year[a,b]	Tg C per year[a,b]		
North American Atlantic Coast (NAAC)					
Scotian Shelf	2.2×10^5	8.3 ± 6.6	1.8	Combination of *in situ* and satellite observations (10-year average, 1999–2008)	Shadwick et al. (2010)
	1.28×10^5	−14 ± 3.2	−1.9	Observation-based estimate (reference year, 2004)	Signorini et al. (2013); using Ho et al. (2011) gas transfer param.
		−5.0 ± 4.3	−0.64	Combination of *in situ* and satellite observations (reference year, 2004)	Signorini et al. (2013); using Ho et al. (2011) gas transfer param.
	1.2×10^5	−28 ± 0.72	−3.3	Model (2-year average, 2004–2005)	Fennel and Wilkin (2009)
Gulf of Maine (without Georges Bank and Nantucket Shoals)	1.28×10^5	0.48 ± 2.6	0.061	Observation-based estimate (reference year, 2004)	Signorini et al. (2013); using Ho et al. (2011) gas transfer param.
		0.12 ± 0.96	0.015	Combination of *in situ* and satellite observations (reference year, 2004)	Signorini et al. (2013); using Ho et al. (2011) gas transfer param.
		4.6 ± 3.1	0.58	Observation-based estimate (5-year mean, 2004–2008)	Vandemark et al. (2011)
Georges Bank and Nantucket Shoals	0.58×10^5	−8.5 ± 2.6	−0.49	Observation-based estimate (reference year, 2004)	Signorini et al. (2013); using Ho et al. (2011) gas transfer param.
		−16 ± 2.9	−0.95	Combination of *in situ* and satellite observations (reference year, 2004)	Signorini et al. (2013); using Ho et al. (2011) gas transfer param.
Gulf of Maine (with Georges Bank and Nantucket Shoals)	1.7×10^5	−20 ± 4.9	−3.4	Model (2-year average, 2004–2005)	Fennel and Wilkin (2009)
	0.87×10^5	−27 ± 8.4	−1.9	Model (4-year average, 2004–2007)	Cahill et al. (2016)

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Table 16.1. Regional Estimates of Net Air-Sea Carbon Dioxide Exchange from Observations and Regional Models[a,b]

Region	Area (km²)	Air-Sea Exchange		Observation-Based Estimate or Model	Reference
		g C per m² per year[a,b]	Tg C per year[a,b]		
Mid-Atlantic Bight (MAB)	1.25×10^5	−13 ± 8.3	−1.6	Observation-based estimate	DeGrandpre et al. (2002)
		−14	−1.8	Model (2004)	Fennel et al. (2008)
	0.93×10^5	−13 ± 3.2	−1.2	Observation-based estimate (reference year, 2004)	Signorini et al. (2013); using Ho et al. (2011) gas transfer param.
		−21 ± 2.3	−2.0	Combination of *in situ* and satellite observations (reference year, 2004)	Signorini et al. (2013); using Ho et al. (2011) gas transfer param.
	0.86×10^5	−11 ± 2.6	−0.92	Model (2-year average, 2004–2005)	Fennel and Wilkin (2009)
	1.15×10^5	−14 ± 2.4	−1.7	Model (4-year average, 2004-2007)	Cahill et al. (2016)
South Atlantic Bight (SAB)	1.02×10^5	−5.8 ± 2.5	−0.59	Observation-based estimate	Jiang et al. (2008)
		−8.2 ± 2.9	−0.83	Observation-based estimate (reference year, 2004)	Signorini et al. (2013); using Ho et al. (2011) gas transfer param.
		−8.0 ± 1.9	−0.82	Combination of *in situ* and satellite observations (reference year, 2004)	Signorini et al. (2013); using Ho et al. (2011) gas transfer param.
	0.92×10^5	−6 ± 2.4	−0.55	Model (4-year average, 2004–2007)	Cahill et al. (2016)
Gulf of Mexico (GMx)					
Whole Gulf of Mexico	15.6×10^5	−2.3 ± 0.96	−3.6	Observation-based estimate	Robbins et al. (2014)
		−8.5 ± 6.5	−13	Model (7-year average, 2005–2010)	Xue et al. (2016)
Open Gulf of Mexico	10.1×10^5	−5.8 ± 0.84	−5.8	Observation-based estimate	Robbins et al. (2014)
		−12 ± 5.5	−13	Model (7-year average, 2005–2010)	Xue et al. (2016)
West Florida Shelf	1.5×10^5	4.4 ± 1.3	0.67	Observation-based estimate	Robbins et al. (2014)
		4.6 ± 0.58	0.68	Model (7-year average, 2005–2010)	Xue et al. (2016)

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Table 16.1. Regional Estimates of Net Air-Sea Carbon Dioxide Exchange from Observations and Regional Models[a,b]

Region	Area (km^2)	Air-Sea Exchange		Observation-Based Estimate or Model	Reference
		g C per m^2 per year[a,b]	Tg C per year[a,b]		
Northern Gulf of Mexico	1.5×10^5	−5.3 ± 4.4	−0.79	Observation-based estimate	Robbins et al. (2014)
		−3.8 ± 8.9	−0.58	Model (7-year average, 2005–2010)	Xue et al. (2016)
	unknown	−11 ± 44		Observation-based estimate	Huang et al. (2015)
	unknown	−13 ± 3.6		Combination of *in situ* and satellite observations	Lohrenz et al. (2018)
Western Gulf of Mexico	0.8×10^5	2.2 ± 0.6	0.17	Observation-based estimate	Robbins et al. (2014)
		4.1 ± 3.8	0.33	Model (7-year average, 2005–2010)	Xue et al. (2016)
Mexico Shelf	1.8×10^5	−1.1 ± 0.6	−0.19	Observation-based estimate	Robbins et al. (2014)
		−2.3 ± 4.2	−0.41	Model (7-year average, 2005–2010)	Xue et al. (2016)
North America Pacific Coast (NAPC)					
Gulf of Alaska	3×10^6	−11	−36	Observations, climatology of 1991–2011, 0 to 400 km offshore	Evans and Mathis (2013)
British Columbia coastal ocean		−35		Observations, 1995–2001	Evans et al. (2012)
British Columbia Vancouver Island shelf		−6		Model, annual average	Ianson and Allen (2002)
Oregon Shelf		−3.6 ± 82		Observations inshore of 200-m isobath	Evans et al. (2011)
Oregon Shelf		−88		Observations	Hales et al. (2005)
50° to 22°N	1.76×10^6	−7.9	−14	Satellite-based prediction of pCO_2 and satellite-based wind speed, within 370 km of coast	Hales et al. (2012)
35° to 40°N			0.6	Model, 0 to 100 km from coast, 1999–2005	Fiechter et al. (2014)
40° to 45°N			−0.4	Model, 0 to 100 km from the coast, 1999–2005	Fiechter et al. (2014)

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Table 16.1. Regional Estimates of Net Air-Sea Carbon Dioxide Exchange from Observations and Regional Models[a,b]

Region	Area (km^2)	Air-Sea Exchange		Observation-Based Estimate or Model	Reference
		g C per m^2 per year[a,b]	Tg C per year[a,b]		
30° to 46°N	1.49×10^6	0.6 ± 2.4	0.9±3.6	Model, 0 to 800 km from the coast, 12-year simulation with climatological forcing	Turi et al. (2014)
North American Arctic (NAA)					
Chukchi Sea	2.9×10^5	−15	−4.4	Observations	Evans et al. (2015b)
	5.95×10^5	−175 ± 44	−38 ± 7	Observations	Bates et al. (2006)
	5.95×10^5	−35	−12.1	Observations	Gao et al. (2012)
		−17 ± 17		Satellite-based prediction of pCO_2 and satellite-based wind speed	Yasunaka et al. (2016)
Beaufort Sea (Amundsen Gulf)		−14		Observations	Shadwick et al. (2011)
Beaufort Sea (Cape Bathurst Polynya)		−44 ± 28		Observations	Else et al. (2013)
Beaufort Sea	9.2×10^5	−4.4	−4.0	Observations	Evans et al. (2015b)
Beaufort Sea		−10 ± 15		Observations	Mucci et al. (2010)
Western Arctic Coastal Ocean	1.2×10^6	−8.8 ± 4.8	−11 ± 5.7	Observations	Evans et al. (2015b)
Hudson Bay	7.32×10^5	−3.2 ± 1.8	−0.58 ± 0.3	Observations	Else et al. (2008)
Bering Sea	6.94×10^5	−9.6	−6.7	Observations	Cross et al. (2014a)
		−5.3	−3.7	Observations	Takahashi et al. (2009)

Notes

a) Positive fluxes indicate a source to the atmosphere.

b) C, carbon; CO_2, carbon dioxide; Tg, teragrams; g, grams; 1 Tg = 10^{12} g.

atmospheric increase in CO_2). Their results suggest that warming and changes in atmospheric forcing have modest impacts on air-sea CO_2 flux in the MAB and GOM compared with that in the SAB where surface warming turns the region from a net sink into a net source of CO_2 to the atmosphere. Model studies also illustrate the effects of interactions between biogeochemical transformations in the sediment and the overlying water column on carbon fluxes. For example, Fennel et al. (2008) showed that the effective alkalinity flux resulting from denitrification in sediments of the North American Atlantic Coast reduces the simulated ocean uptake of CO_2 by 6% compared to a simulation without sediment denitrification.

The passive-margin sediments along the Atlantic coast have not been considered an area of significant CH_4 release until recently (Brothers et al., 2013; Phrampus and Hornbach 2012; Skarke et al., 2014). Phrampus and Hornbach (2012) predicted that

massive seepage of CH_4 from upper-slope sediments is occurring in response to warming of intermediate-depth Gulf Stream waters. Brothers et al. (2013) and Skarke et al. (2014) documented widespread CH_4 plumes in the water column and attributed them to gas hydrate degradation. Estimated CH_4 efflux from the sediment in this region ranges from 1.5×10^{-5} to 1.8×10^{-4} Tg CH_4 per year, where the uncertainty range reflects different assumptions underlying the conversion from CH_4 plume observations to seepage rates. The fraction of the released CH_4 that escapes to the atmosphere remains uncertain (Phrampus and Hornbach 2012).

16.3.2 North American Pacific Coast

The North American Pacific Coast extends from Panama to the Gulf of Alaska and is an active margin with varying shelf widths (see Figure 16.1, p. 651). The continental shelf is narrow along the coasts of California, Oregon, and Washington, with a width on the order of 10 km but widening significantly in the Gulf of Alaska, where shelves extend up to 200 km offshore. In the Gulf of Alaska, freshwater and tidal influences strongly affect cross-shelf exchange, and the shelf is dominated by downwelling circulation. The region from Vancouver Island to Baja California is a classic eastern boundary current upwelling region influenced by the California Current System (Chavez et al., 2017). Winds drive a coastal upwelling circulation characterized by equatorward flow in the California Current and by coastal jets and their associated eddies and fronts that extend offshore, particularly off the coasts of Baja California, California, Washington, and Oregon. The northern California Current System experiences strong freshwater influences and seasonality in wind forcing that diminish in the southern part of the system. In addition to the Columbia River and the Fraser River, a variety of small mountainous rivers, with highly variable discharge, supply freshwater. The Central American Isthmus runs from Panama to the southern tip of Baja California and experiences intense and persistent wind events, large eddies, and high waves that combine to produce upwelling and strong nearshore mixing (Chapa-Balcorta et al., 2015; Franco et al., 2014). In addition to alongshore winds, strong seasonal wind jets that pass through the Central American cordillera create upwelling "hotspots" and drive production during boreal winter months in the gulfs of Tehuantepec, Papagayo, and Panama (Chapa-Balcorta et al., 2015; Chelton et al., 2000a, 2000b; Gaxiola-Castro and Muller-Karger 1998; Lluch-Cota et al., 1997). The California Current brings water from the North Pacific southward into the southern California and Central American Isthmus regions, while the California Undercurrent transports equatorial waters northward in the subsurface.

The net exchange of CO_2 with the atmosphere across the North American Pacific Coast is characterized by strong spatial and temporal variation and reflects complex interactions between biological uptake of nutrients and degassing of nutrient- and carbon-rich upwelled waters. A growing number of coastal air-sea flux studies have used extrapolation techniques to estimate fluxes across the coastal ocean on regional to continental scales. Observation-based studies of air-sea CO_2 flux suggest that estimates for the coastal ocean from Baja California to the Gulf of Alaska range from a weak to moderate sink of atmospheric CO_2 over this broad longitudinal range. Central California coastal waters have long been understood to have near-neutral air-sea CO_2 exchange because of their large and counter-balancing periods of efflux during upwelling conditions and influx during periods of relaxation and high primary productivity; this pattern is strongly modulated by El Niño–La Niña conditions (Friederich et al., 2002). Hales et al. (2005) used seasonal data to estimate an uptake of 88 g C per m^2 per year by Oregon coastal waters, which is about 15 times larger than the global mean of 6 g C per m^2 per year. Using data with greater temporal coverage, Evans et al. (2011) showed how large flux events can significantly alter the estimation of net exchanges for the Oregon shelf. After capturing a large and short-lived efflux event, their annual estimate was outgassing of 3.1 ± 82 g C per m^2 per year for this same region. The disparity illustrates the importance of basing regional flux estimates on observations that are well resolved in time and space. Capitalizing on

the increased and more uniform spatiotemporal coverage of satellite data, Hales et al. (2012) estimated an annual mean uptake of 7.9 g C per m^2 per year between 22° and 50°N within 370 km offshore. The most northern estimates for the North American Pacific Coast by Evans et al. (2012) and Evans and Mathis (2013) determined influxes of 26 g C per m^2 per year for British Columbian coastal waters shoreward of the 500-m isobath and 18 g C per m^2 per year for Gulf of Alaska coastal waters shoreward of the 1500-m isobath.

Models for the upwelling region (Fiechter et al., 2014; Turi et al., 2014) reproduce the pattern of CO_2 outgassing nearshore and CO_2 uptake further offshore. They also illustrate the intense eddy-driven variability nearshore. Turi et al. (2014) simulate a weak source of 0.6 ± 2.4 g C per m^2 per year for the region from 30° to 46°N, extending 800 km of shore, an amount which is inconsistent with the observations of Hales et al. (2012) that describe the same region as a sink of 7.9 g C per m^2 per year. Fiechter et al. (2014) simulate a source of atmospheric CO_2 of 0.6 Tg C per year for the region from 35° to 45°N within 600 km of shore, an estimate which is in contrast to the observation-based estimate of a 14 Tg C sink published by Hales et al. (2012). Both models simulate strong outgassing within the first 100 km of shore, driven by intense upwelling of nutrient- and carbon-rich water, compensated by biologically driven CO_2 uptake from the atmosphere as upwelled nutrients are consumed by photosynthesis during subsequent offshore advection within several hundreds of kilometers of the coast. The disagreement in mean simulated fluxes may result partly from different choices of averaging region and period and differences in model forcing, such as the climatological forcing in Turi et al. (2014) versus realistic variability in Fiechter et al. (2014). Notable, however, is that observations for the Oregon shelf by Evans et al. (2015a) showed intense summer upwelling that led to strong outgassing with pronounced variability in air-sea fluxes but found only weak stimulation of primary production. The research team hypothesized that nutrient-rich waters might be subducted offshore at convergent surface temperature fronts before nutrients are fully consumed by primary producers.

Less is known about the air-sea flux of CH_4 along the North American Pacific Coast margin. Recent studies inventoried sedimentary sources of CH_4 hydrates, derived from terrestrial and coastal primary production, and suggested that extensive deposits along the Cascadia margin are beginning to destabilize because of warming (Hautala et al., 2014; Johnson et al., 2015).

Cross-shelf exchange of carbon occurs in the California Current System mostly in response to wind-driven circulation and eddies, but river plumes and tides also have been shown to increase offshore transport in the northern part of the system (Barth et al., 2002; Hales et al., 2006). Uncertainties in published estimates are high, ranging from very small (Ianson and Allen 2002; Pennington et al., 2010) to very high fractions of primary production (Hales et al., 2005; Turi et al., 2014), again as a result of the region's large spatial and temporal variability.

16.3.3 Gulf of Mexico

The Gulf of Mexico (GMx) is a semi-enclosed marginal sea at the southern coast of the conterminous United States. The passive margin shelves of its northern portion are relatively wide (up to 250 km west of Florida), but, in contrast to shelf waters of the North American Atlantic Coast, those of the GMx are not separated from open-ocean waters by shelf-break fronts or currents. Ocean water enters the Gulf mainly through the Yucatan Channel, where it forms the northeastward meandering Loop Current (LC), which sheds anticyclonic eddies and exits the Gulf through the Florida Straits (Muller-Karger et al., 2015; Rivas et al., 2005). While shelf circulation is influenced primarily by local wind and buoyancy forcing, outer-shelf regions are at times influenced by LC eddies that impinge on and interact with the shelf (Lohrenz and Verity 2004). Riverine input is substantial in the northern GMx, where the Mississippi-Atchafalaya River System delivers large loads of freshwater, nutrients, and sediments.

Observational estimates indicate that the GMx, as a whole, is a weak net sink of atmospheric CO_2 with an annual average of 2.3 ± 0.96 g C per m^2 per year (Robbins et al., 2014). Robbins et al. (2014) also provide flux estimates, as follows, for smaller shelf regions, namely, the West Florida Shelf, the northern Gulf shelf, the western Gulf shelf, and the Mexico shelf. The West Florida Shelf and western Gulf shelf act as sources to the atmosphere, with estimated annual average fluxes of 4.4 ± 1.3 and 2.2 ± 0.6 g C per m^2 per year, respectively. The northern Gulf acts as a sink, with an estimated flux of 5.3 ± 4.4 g C per m^2 per year, and the Mexican shelf is almost neutral, with an estimated flux of 1.1 ± 0.6 g C per m^2 per year. Huang et al. (2015) estimated a larger uptake on the northern Gulf shelf of 11 ± 44 g C per m^2 per year (i.e., about twice the estimate of Robbins et al., 2014) and reported a much larger uncertainty. In an analysis that combines satellite and *in situ* observations, Lohrenz et al. (2018) estimated a similar uptake for the northern GMx of 13 ± 3.6 g C per m^2 per year. The overall carbon exchanges in the Gulf vary significantly from year to year because of interannual variability in wind, temperature, and precipitation (Muller-Karger et al., 2015).

Model-simulated air-sea CO_2 fluxes by Xue et al. (2016) agree relatively well with the estimates of Robbins et al. (2014), reproducing the same spatial pattern though their simulated Gulf-wide uptake of 8.5 ± 6.5 g C per m^2 per year is larger. This discrepancy results largely from a greater simulated sink in the open Gulf. Also, the uncertainty estimates of the model-simulated fluxes by Xue et al. (2016) are much larger than those of Robbins et al. (2014); the latter might be too optimistic in reporting uncertainties of the flux estimates.

Overall, the various observation- and model-derived estimates for Gulf regions agree in terms of their broad patterns, but existing discrepancies and, at times, large uncertainties indicate that current estimates need further refinement.

Quantitative understanding of CH_4 dynamics in GMx coastal and oceanic environments is limited. Solomon et al. (2009) speculated that deep CH_4 hydrate seeps in the Gulf potentially are a significant CH_4 source to the atmosphere. They estimated ocean-atmosphere fluxes from seep plumes of 1,150 ± 790 to 38,000 ± 21,000 g CH_4 per m^2 per day compared with 2.2 ± 2.0 to 41 ± 8.2 g CH_4 per m^2 per day for background sites. Subsequent acoustic analyses of bubble plume characteristics question the finding that CH_4 bubbles make their way to the surface (Weber et al., 2014), and the fate of CH_4 emissions from seeps and their overall contribution to atmospheric CH_4 remain uncertain.

16.3.4 North American Arctic

The North American Arctic coastal ocean comprises broad (~300 km) shallow shelves in the Bering and Chukchi seas, the narrower (<100-km) Beaufort Sea shelf, the Hudson Bay, and the extensive Canadian Arctic Archipelago (CAA). Shelf water enters these regions from the North Pacific and follows a large-scale pathway from its entrance into the North American Arctic through the Bering Strait via the Chukchi and Beaufort seas into the CAA and, ultimately, the North Atlantic (Carmack et al., 2006, 2015). Hudson Bay receives significant inputs of freshwater (Dery et al., 2005). Except for the southernmost Bering Sea, most of the coastal region is covered with sea ice from about October to June. Areas of persistent multiyear sea ice at the northernmost extent of the CAA are rapidly declining (Stroeve et al., 2012). Reoccurring polynyas (i.e., holes in the ice) are found in all three of its major regions (Smith and Barber 2007). The North American Arctic is sparsely populated with communities heavily reliant on subsistence fishing and hunting; the rapid regional changes associated with global warming are affecting these communities. Globally, the pace of increasing air temperatures is the highest in the North American Arctic and adjacent Arctic regions, resulting in significant reductions in both summer and winter sea ice cover that profoundly affect the marine ecosystems across the northern extent of the continent (Moore and Stabeno 2015; Steiner et al., 2015).

Coastal waters in the North American Arctic have been described consistently as a net sink for

atmospheric CO_2 (Bates et al., 2006, 2011; Chen et al., 2013; Cross et al., 2014a; Dai et al., 2013; Else et al., 2008; Evans et al., 2015b; Laruelle et al., 2014; Mucci et al., 2010; Shadwick et al., 2011). This general trait is caused by low surface water pCO_2, the partial pressure of CO_2, relative to the atmosphere during ice-free months. These levels are set by the combination of low water temperatures and seasonally high rates of both ice-associated and open-water primary production (Cai et al., 2010b, 2014; Steiner et al., 2014), as well as by limited gas exchange through sea ice relative to open water (Butterworth and Miller 2016; Rutgers van der Loeff et al., 2014) during winter months when under-ice pCO_2 is higher. Suppressed gas exchange through sea ice has been a source of debate within the Arctic CO_2 flux community, likely a result of inconsistencies between methodologies and the challenge of data collection in such a harsh environment, particularly during winter. The typical approach of calculating air-sea CO_2 flux (from measured air-sea pCO_2 differences and gas transfer rates parameterized using wind speed relationships) can differ markedly from flux estimations determined by eddy correlations. The latter suggest high rates of CO_2 exchange relative to open-water fluxes (Else et al., 2011). Three arguments indicate that the high, initial eddy correlation–based fluxes may be overestimates: 1) the potential for unaccounted CO_2 and water vapor cross-correlation possibly affecting the measurement (Landwehr et al., 2014); 2) independent analysis of the ^{222}Radon isotope showing near-zero gas exchange in areas covered by sea ice (Rutgers van der Loeff et al., 2014); and 3) recent demonstration of dampened gas-transfer velocities via concurrent, properly corrected eddy covariance–based fluxes and air-sea pCO_2 difference measurements in the Antarctic marginal ice zone supporting linear scaling methods that calculate fluxes using percent sea ice cover (Butterworth and Miller 2016).

However, despite the dampening effect of sea ice, its permeability is a known function of temperature (Golden et al., 2007). Therefore, as Arctic winter temperatures continue to rise, the role of wintertime air-ice CO_2 exchange may become increasingly important because rising temperatures may allow some degree of exchange to take place. To date, measurements of wintertime exchange have been limited to very few studies (Else et al., 2011, 2013; Miller et al., 2015). In recent years, the role of sea ice growth and decay has been shown to significantly affect the air-sea CO_2 flux (Rysgaard et al., 2007, 2009). During sea ice formation, brine rejection forms dense high-saline water that is exported from the surface layer. This process alters the ratio of total alkalinity to sea ice DIC and the underlying seawater, because DIC is a component of the brine whereas total alkalinity precipitates in the brine channels as a form of $CaCO_3$ known as ikaite (Dieckmann et al., 2008; Rysgaard et al., 2013). During sea ice decay, ikaite dissolves, leading to excess total alkalinity relative to DIC and undersaturation of CO_2 in meltwater.

Estimates of air-sea CO_2 flux in the Chukchi and Beaufort seas, Hudson Bay, and the western CAA all indicate atmospheric CO_2 uptake (Bates et al., 2006; Else et al., 2008, 2013; Gao et al., 2012; Mucci et al., 2010; Semiletov et al., 2007; Shadwick et al., 2011; see Table 16.1, p. 657) with significantly higher uptake over the broad and productive Chukchi shelf. A recent synthesis of a decade of coastal ocean data collected within 400 km of land determined an annual mean uptake of 8.8 g C per m^2 per year (Evans et al., 2015b). Variability in wind patterns and sea ice cover affects the water column structure and connectivity between the surface ocean and overlaying atmosphere, thus influencing the magnitude of air-sea CO_2 exchange.

With regard to Arctic CH_4 fluxes, much more is known about the emission potential, distribution, and functioning of terrestrial sources (McGuire et al., 2009); knowledge of marine CH_4 sources is developing slowly due to sparse observations and the logistical challenges of Arctic marine research. The largest marine CH_4 source in the Arctic is dissociation of gas hydrates stored in continental margin sediments (Parmentier et al., 2013, 2015). As sea ice continues to retreat and ocean waters warm, CH_4 hydrate stability is expected to decrease

Table 16.2. Regional Estimates of Net Air-Sea Carbon Dioxide Exchange from Two Data Syntheses and a Process-Based Model for the MARCATS Regions[a,b]

MARCATS Segment No.[b]	MARCATS System[b]	Class	Shelf Area (10^3 km^2)	Chen et al. (2013)	Laruelle et al. (2014)	Bourgeois et al. (2016)
				Flux[a,b] (Tg C per year)	Flux[a,b] (Tg C per year)	Flux[a,b] (Tg C per year)
1	Northeastern Pacific	Subpolar	460	−19	−6.8	−10 ± 0.82
2	California Current	Eastern Boundary Current	210	−5.7	−0.13	−0.48 ± 0.15
3	Tropical Eastern Pacific	Tropical	200	−0.1	0.19	−0.22 ± 0.095
9	Gulf of Mexico	Marginal Sea	540	−1.3	−2.1	−4.5 ± 0.63
10	Florida Upwelling	Western Boundary Current	860	−11	−2.7	−15 ± 1.3
11	Labrador Sea	Subpolar	400	−10	−19	−8.8 ± 1.2
12	Hudson Bay	Marginal Sea	1100	11	NA	−3.8 ± 3.4
13	Canadian Arctic Archipelago	Polar	1200	−57	−14	−6.2 ± 0.75
	Total		4900	−94	−44	−49

Notes

a) Positive fluxes indicate a source to the atmosphere.

b) MARCATS, MARgins and CATchments Segmentation; C, carbon; CO_2, carbon dioxide; Tg, teragrams; g, gram; Tg = 10^{12} g

with potentially large and long-term implications. An additional potential marine CH_4 source, unique to polar settings, is release from subsea permafrost layers, with fluxes from thawed sediments reported to be orders of magnitude higher than fluxes from adjacent frozen sediments (Shakhova et al., 2015).

16.3.5 Summary Estimates for CO_2 Uptake by North American Coastal Waters

Despite the variability in regional estimates discussed above and summarized in Table 16.1, p. 657, North American coastal waters clearly act as a net sink of atmospheric carbon. Because of discrepancies among studies, these various regional estimates would be difficult to combine into one number with any confidence. Instead, this chapter considers estimates of net air-sea CO_2 exchange in North American coastal waters from two global data syntheses (Chen et al., 2013; Laruelle et al., 2014) and a process-based global model (Bourgeois et al., 2016; see Table 16.2, this page). The data syntheses use a global segmentation of the coastal zone and associated watersheds known as MARCATS (MARgins and CATchments Segmentation; Laruelle et al., 2013), which, at a resolution of 0.5°, delineates a total of 45 coastal segments, eight of which surround North America. The data synthesis of Chen et al. (2013) is a summary of individual studies, whereas Laruelle et al. (2014) analyze the Surface Ocean CO_2 Atlas 2.0 database (Bakker et al., 2014) to derive regional estimates. The data syntheses of Chen et al. (2013) and Laruelle et al. (2014)

estimate the North American coastal uptake to be 94.4 and 44.5 Tg C per year, respectively, and the process-based model of Bourgeois et al. (2016) estimates an uptake of 48.8 Tg C per year (see Table 16.2, p. 665). Although there are significant regional discrepancies between the latter two estimates for the eastern tropical Pacific Ocean (i.e., the Central American Isthmus), the GMx, the Florida Upwelling region (actually covering the eastern United States), the Labrador Sea, and the CAA, the overall flux estimates for North America are in close agreement. This, and the fact that Laruelle et al. (2014) used a consistent methodology to estimate air-sea CO_2 flux, builds some confidence in these numbers.

The net CO_2 flux and its anthropogenic component from the process-based global model of Bourgeois et al. (2016) are also reported for a regional decomposition of the EEZs of the United States, Canada, and Mexico (see Table 16.3, this page) in Table 16.4, p. 667. The model simulates a net uptake of CO_2 in North American EEZ coastal waters (excluding the EEZ of the Hawaiian and other islands) of 160 Tg C per year with an anthropogenic flux contribution of 59 Tg C per year. This chapter adopts 160 Tg C per year as the net uptake by coastal waters of North America, excluding tidal wetlands and estuaries. Unfortunately, there are no formal error estimates for this uptake. Instead, estimates adopted here project an error by first noting that the Bourgeois et al. (2016) model is in good agreement with the more recent of the two observation-based estimates for the MARCATS regions of North America. Furthermore, the error estimate for the uptake by continental shelves globally is about 25%, with the North American MARCATS regions having mainly "fair" data quality (Laruelle et al., 2014). Hence, assuming an error of ±50% for the uptake by North American EEZ waters seems reasonable.

Table 16.3. Subregions of the Combined Exclusive Economic Zone of Canada, the United States, and Mexico[a]

Region Number	Area (10^3 km^2)	Acronym	Name
1	500	MAB	Mid-Atlantic Bight
2	160	GOM	Gulf of Maine
3	220	SS	Scotian Shelf
4	860	GStL	Gulf of St. Lawrence and Grand Banks
5	1,100	LS	Labrador Shelf
6	1,200	HB	Hudson Bay
7	1,000	CAA	Canadian Arctic Archipelago
8	950	BCS	Beaufort and Chukchi Seas
9	2,200	BS	Bering Sea
10	1,500	GAK	Gulf of Alaska
11	460	CCSN	Northern California Current System
12	640	CCSC	Central California Current System
13	1,200	CCSS	Southern California Current System
14	1,400	Isthmus	Isthmus
15	1,600	GMx	Gulf of Mexico and Yucatan Peninsula
16	500	SAB	South Atlantic Bight
17	7,500	Islands	Hawai'i and other Pacific and Caribbean islands

Notes

a) Area is calculated for the mask that was used to define subregions for averaging.

16.3.6 Summary Carbon Budget for North American Coastal Waters

Combining the atmospheric CO_2 uptake estimate with estimates of carbon transport from land and carbon burial in ocean sediments enables a first attempt at constructing a carbon budget for the North American EEZ (see Table 16.5, p. 668). Carbon delivery to the coastal ocean from land via rivers and from tidal wetlands after estuarine processing (i.e., CO_2 outgassing and carbon burial in estuaries) is estimated to be 106 ± 30 Tg C per year (see Ch. 15:

Table 16.4. Estimates of Carbon Burial and Primary Production,[a] Net Primary Production (NPP),[b] and Simulated NPP and Air-Sea Exchange of Carbon Dioxide[c] for the Exclusive Economic Zone Decomposition in Table 16.2[d,e,g]

Region[f]	Carbon Burial[a]		Satellite NPP[a]		Satellite NPP[b]	NPP from Global Model[c]		Air-Sea Exchange of CO_2[c]	
Number and Acronym	g C per m² per year	Tg C per year	g C per m² per year	Tg C per year	Tg C per year	g C per m² per year	Tg C per year	g C per m² per year	Tg C per year
1, MAB	23	101	360	170	170	260	120	31 (14)	15 (6.8)
2, GOM	46	5.5	490	58	81	180	26	33 (7.1)	4.9 (1.1)
3, SS	9.8	2.0	300	63	64	170	43	33 (11)	8.2 (2.8)
4, GStL	16	11	260	190	230	150	130	24 (6.5)	21 (5.6)
5, LS	2.3	2.3	120	120	70	82	88	33 (9.5)	36 (10)
6, HB	19	17.1	144	130	13	130	150	–0.48 (1.4)	–0.50 (1.7)
7, CAA	2.6	1.6	42	26	Not available	19	20	4.1 (0.96)	4.3 (0.96)
8, BCS	12	10	120	110	Not available	49	47	8.0 (1.2)	7.6 (1.1)
9, BS	17	34	240	490	470	130	270	13 (4.0)	28 (8.6)
10, GAK	7.2	10.0	260	360	420	130	210	19 (4.6)	29 (7.1)
11, CCSN	6.1	2.54	270	110	150	160	73	9.4 (4.2)	4.3 (1.9)
12, CCSC	1.2	0.65	260	150	210	170	110	1.1 (4.4)	0.72 (2.9)
13, CCSS	0.99	1.1	210	230	280	150	190	–4.3 (3.1)	–5.5 (4.0)
14, Isthmus	0.42	0.53	230	300	210	150	200	–2.3 (3.6)	–3.2 (4.9)
15, GMx	6.2	8.7	250	350	390	220	360	4.8 (3.7)	7.9 (6.2)
16, SAB	5.4	2.4	210	92	110	260	130	9.7 (6.6)	5.0 (3.4)
17, Islands	0.0055	0.041	120	890	580	80	620	–1.4 (4.1)	–11 (31)
Total	NA	120	NA	3,400	NA	NA	2,800	NA	150 (100)
Total w/o 17	NA	120	NA	2,500	NA	NA	2,200	NA	160 (59)

Notes

a) Dunne et al. (2007).

b) Balcom and Continental Shelf Associates (2011).

c) Bourgeois et al. (2016).

d) Included in carbon dioxide (CO_2) exchange estimates are total and anthropogenic fluxes calculated by averaging the model years 1993–2012. Here all fluxes are relative to the coastal ocean reservoir (i.e., positive fluxes are a source to the coastal ocean, while negative fluxes are a sink).

e) NPP, net primary production; g, grams; C, carbon; Tg, teragrams.

f) See Table 16.3, p. 666, for region descriptions.

g) Key: g C, grams of carbon; Tg C, teragrams of carbon.

Tidal Wetlands and Estuaries, p. 596). Estimates of carbon burial, based on the method of Dunne et al. (2007) for the regional decomposition of the North American EEZ, are reported in Table 16.4, p. 667, with a total flux of 120 Tg C per year. Here these fluxes are considered to be an upper bound because they are substantially larger than other estimates. The Dunne et al. (2007) global estimates of organic carbon burial in waters shallower than 200 m are 19 ± 9 g C per m^2 per year, much larger than the estimates of 6 and 1 g C per m^2 per year by Chen (2004) and Muller-Karger et al. (2005), respectively, although areas are slightly different in the three studies. The organic carbon burial estimates of Dunne et al. (2007) for the GOM, MAB, and SAB (see Table 16.4, p. 667) are larger by factors of 8, 17, and 3, respectively, than the best estimates of the empirical model of Najjar et al. (2018). However, due to different definitions of the boundary between coastal waters and the open ocean, the combined area of the GOM, MAB, and SAB in Najjar et al. (2018) is about a third of that in Dunne et al. (2007). Finally, Dunne et al. (2007) estimated the organic carbon burial in Hudson Bay to be 19 g C per m^2 per year, compared to a mean estimate of 1.5 ± 0.7 g C per m^2 per year of burial from sediment cores (Kuzyk et al., 2009). Given these results, SOCCR2 considers the estimates of Dunne et al. (2007) to be an upper bound and assumes that a reasonable lower bound is about an order of magnitude smaller, thus placing the North American organic carbon burial estimate at 65 ± 55 Tg C per year.

If these estimates of net air-sea flux, carbon burial, and carbon input from land are accurate, then the residual must be balanced by an increase in carbon inventory in coastal waters and a net transfer of carbon from coastal to open-ocean waters. In their global compilation, Regnier et al. (2013) report an increase in the coastal carbon inventory of 50 Tg C per year, which is a quarter of their estimated anthropogenic carbon uptake by air-sea exchange in the coastal waters of 200 Tg C per year. The latter estimate is uncertain. In their global modeling study, which did not account for anthropogenic changes in carbon delivery from land, Bourgeois et al. (2016) estimated an accumulation of carbon in the coastal ocean of 30 Tg C per year. This amount is a third of their estimated uptake of anthropogenic carbon from air-sea gas exchange in the coastal ocean of 100 Tg C per year and approximately half of their estimated cross-shelf export of anthropogenic carbon of 70 Tg C per year. The rate of carbon accumulation in the North American EEZ from the model of Bourgeois et al. (2016) is 50 Tg C per year (see Table 16.5, this page). Here again, this chapter assumes an uncertainty of ±50%. The residual of 151 ± 105 Tg C per year is the inferred export of carbon to the open ocean (see Table 16.5, this page). The fact that the error in this residual is large in absolute and relative terms emphasizes the need for more accurate carbon budgets for coastal waters of North America. The challenge, however, is that many of these terms are small compared to internal carbon cycling in coastal waters, which is dominated by primary production and respiration. Two separate estimates of primary production (see Table 16.4, p. 667) are in broad agreement and reveal that terms in the Table 16.5 budget are just a few percent of primary

Table 16.5. Approximate Summary Carbon Budget for the Exclusive Economic Zone of North America[a–d]

Process	Flux (Tg C per year)[b,d]
Input from land	106 ± 30
Uptake from atmosphere	160 ± 80
Burial	–65 ± 55
DIC[c] accumulation in coastal waters	–50 ± 25
Inferred open-ocean export (residual)	–151 ± 105

Notes

a) Exclusive Economic Zone (EEZ) excludes EEZs of the Hawaiian and other islands.

b) Positive fluxes are a source to the coastal ocean, while negative fluxes are a sink.

c) The accumulation of dissolved inorganic carbon (DIC) is reported with a negative sign to illustrate that all fluxes balance.

d) Tg C, teragrams of carbon.

production. This also emphasizes that small changes in carbon cycling in coastal waters can result in large changes in atmospheric uptake and transport to the open ocean.

16.4 Climate Trends and Feedbacks

16.4.1 Trends in Coastal Carbon Fluxes

Important questions with respect to coastal carbon fluxes include:

- What is the anthropogenic component of the CO_2 sink?
- How will the coastal ocean change as a CO_2 sink?
- How will changing climate and other forcings affect the total and anthropogenic flux proportions?

As stated in Section 16.2, p. 652, when considering the ocean's role in sequestering anthropogenic carbon, the relevant component is anthropogenic flux, not the total uptake flux. Neither quantifying the anthropogenic carbon flux component nor predicting its future trend is straightforward. Here the likely trends in total carbon fluxes are described; by definition, changes in total carbon fluxes imply changes in anthropogenic fluxes as well.

A direct effect of increasing atmospheric CO_2 will be an increase in net uptake by the coastal ocean. In addition to rising atmospheric CO_2 levels, changes in climate forcings (i.e., surface heat fluxes, winds, and freshwater input) may affect carbon fluxes in North American coastal waters. Ocean warming reduces the solubility of gases and thus directly affects gas concentrations near the surface; this likely will decrease the net air-sea flux of CO_2 by reducing the undersaturation of CO_2 (see Cahill et al., 2016, for the North American Atlantic Coast). Surface temperature increases also strengthen vertical stratification and thus impede vertical mixing, effects which will affect upward diffusion of nutrients and DIC. Enhanced stratification, therefore, could lead to decreases in both biologically driven carbon uptake and CO_2 outgassing. However, model projections for the northern GMx show that the direct effect of increasing atmospheric CO_2 overwhelms the other more secondary effects (Laurent et al., 2018). Furthermore, temperature trends in coastal waters around North America show complex patterns with some regions having cooled from 1982 to 1997 followed by warming from 1997 to 2013 (e.g., the MAB), some regions having warmed from 1982 to 1997 followed by cooling from 1997 to 2013 (e.g., the SAB and Gulf of Alaska), and other regions showing no consistent warming from 1982 to 2013 (e.g., the NAA; Liao et al., 2015). Temperature anomalies from a time series in the central California Current System show warm surface waters for the decade prior to 1997 followed by a prolonged cooler period until the strong surface warming associated with a marine heatwave and the 2015 to 2016 El Niño interrupted the cool anomalies (Chavez et al., 2017). However, deeper waters in the California Undercurrent have shown a multidecadal trend (1980 to 2012) toward warmer, saltier, lower-oxygen, and higher-CO_2 waters at a depth associated with increased northward transport of Pacific equatorial waters (Meinvielle and Johnson 2013).

Some studies suggest that trends in the air-sea pCO_2 gradient (ΔpCO_2) are indicative of a strengthening or weakening of the net CO_2 uptake by shelf systems, where an increasing ΔpCO_2, implying that ocean pCO_2 rises more slowly than atmospheric pCO_2, corresponds to increased net uptake and cross-shelf export (Laruelle et al., 2018). In their observation-based analysis of decadal trends in shelf pCO_2, Laruelle et al. (2018) found that coastal waters lag compared to the rise in atmospheric CO_2 in most regions. For North American coastal waters, they found that the MAB has an increase in ΔpCO_2 of 1.9 ± 3.1 microatmospheres (μatm) per year, a finding which means that in this region surface ocean pCO_2 does not increase or else increases at a rate that is substantially slower than in the atmosphere. For the shelves of the Labrador Sea, the Vancouver Shelf, and the SAB, they found rates of 0.68 ± 0.61 μatm per year, 0.83 ± 1.7 μatm per year, and 0.51 ± 0.74 μatm per year, respectively, implying that surface ocean pCO_2 does not increase or increases at a slower rate than atmospheric CO_2. The only North

American coastal region that exhibits a negative trend is the Bering Sea, with –1.1 ± 0.74 μatm per year, meaning that surface ocean pCO_2 increases at a faster rate than in the atmosphere. Laruelle et al. (2018) concluded that the lag in coastal ocean pCO_2 increase compared to that in the atmosphere in most regions indicates an enhancement in the coastal uptake and export of atmospheric CO_2, although they did not investigate alternative explanations.

Trends in coastal ocean uptake of pCO_2 are highly variable regionally and result from a complex interplay of factors. In coastal upwelling systems, surface warming will increase the horizontal gradient between cold, freshly upwelled source waters and warm, offshore surface water, leading to a greater tendency for the subduction of upwelled water at offshore surface temperature fronts during periods of persistent and strong upwelling-favorable winds. The cumulative effect of these processes for the North American Pacific Coast may be greater and more persistent CO_2 outgassing nearshore and lower productivity offshore as upwelled nitrate is exported before it can be used by the phytoplankton community (Evans et al., 2015a). Rates of warming clearly are faster in higher latitudes, but predicting the net effect of these warming-induced changes in the North American Arctic is not easy. Furthermore, warming in the Arctic leads to reductions in ice cover and longer ice-free periods, both of which directly affect air-sea gas exchange (Bates and Mathis 2009). Another profound effect of Arctic warming is the melting of permafrost, which leads to the release of large quantities of CH_4 to the atmosphere, from both the land surface and the coastal ocean (Crabeck et al., 2014; Parmentier et al., 2013).

Changes in wind stress also directly affect air-sea gas fluxes because stronger winds intensify gas exchange. For example, for the North American Atlantic Coast, changes in wind stress were shown to significantly modify air-sea fluxes (Cahill et al., 2016; Previdi et al., 2009). Large-scale changes in wind patterns also affect ocean circulation with a range of implications (Bakun 1990). Upwelling-favorable winds along the North American Pacific Coast have intensified in recent years, especially in the northern parts of the upwelling regimes (García-Reyes et al., 2015; Rykaczewski and Checkley 2008; Rykaczewski et al., 2015; Sydeman et al., 2014), a change which has led to 1) shoaling of subsurface nutrient-rich waters (Aksnesa and Ohman 2009; Bograd et al., 2015), 2) increased productivity (Chavez et al., 2011, 2017; Jacox et al., 2015; Kahru et al., 2015), 3) higher DIC delivery to the surface (Turi et al., 2016), and 4) declining oxygen levels (Crawford and Peña 2016; Peterson et al., 2013; Bograd et al., 2015). In the North American Arctic, late-season air-sea CO_2 fluxes may become increasingly more directed toward the atmosphere as Arctic low-pressure systems with storm-force winds occur more often over open water, thus ventilating CO_2 respired from the high organic carbon loading of the shallow shelf (Evans et al., 2015b; Hauri et al., 2013; Steiner et al., 2013) and affecting net annual exchanges. The intense warming observed across the North American Arctic also influences mid-latitude weather patterns (Kim et al., 2014), with probable cascading effects on CO_2 exchanges through adjustments in the wind field.

16.4.2 Acidification Trends in North America's Coastal Ocean

Increasing atmospheric CO_2 emissions lead to rising atmospheric CO_2 levels (see Figure 16.3, p. 671) and a net ocean uptake of CO_2. Since about 1750, the ocean has absorbed 27% of anthropogenic CO_2 emissions to the atmosphere from fossil fuel burning, cement production, and land-use changes (Canadell et al., 2007; Le Quéré et al., 2015; Sabine and Tanhua 2010). As a result of this uptake, the surface ocean pCO_2 has increased (see Figure 16.3, p. 671) and oceanic pH, carbonate ion concentration, and carbonate saturation state have decreased (Caldeira and Wickett 2003; Feely et al., 2004, 2009; Orr et al., 2005). Commonly called ocean acidification, this suite of chemical changes is defined more precisely as "any reduction in the pH of the ocean over an extended period, typically decades or longer, that is caused primarily by uptake of CO_2 from the atmosphere but also can be caused by other chemical additions or subtractions from the ocean" (IPCC 2011, p. 37). In addition to uptake of

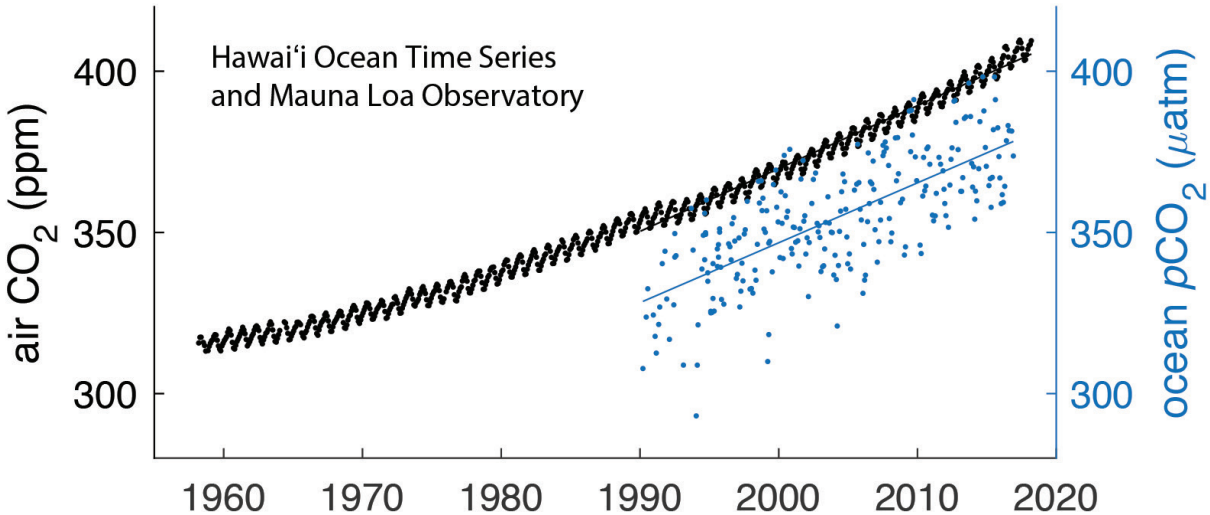

Figure 16.3. Trends in Measured Atmospheric Carbon Dioxide (CO_2) and Surface Ocean Partial Pressure of CO_2 (pCO_2). Black dots represent atmospheric CO_2 measured in parts per million (ppm) at the Mauna Loa Observatory in Hawai'i beginning in 1958. Surface ocean pCO_2 data (blue dots) are measured in microatmospheres (µatm) from the Hawai'i Ocean Time-series (HOT) station near Hawai'i (see Figure 16.4, p. 672, for site location). Black and blue lines indicate linear trends after 1990. Atmospheric CO_2 increased by 1.86 ppm per year; surface ocean pCO_2 increased by 1.95 µatm per year. [Data sources: Mauna Loa, www.esrl.noaa.gov/gmd/ccgg/trends/data.html; HOT, hahana.soest.hawaii.edu/hot/hot-dogs/interface.html.]

CO_2 from the atmosphere, variations in DIC concentrations and thus pH can be caused by biological production and respiration. Ocean acidification can significantly affect growth, metabolism, and life cycles of marine organisms (Fabry et al., 2008; Gattuso and Hansson 2011; Somero et al., 2016) and most directly affects marine calcifiers, organisms that precipitate $CaCO_3$ to form internal or external body structures. When the carbonate saturation state decreases below the equilibrium point for carbonate precipitation or dissolution, conditions are said to be corrosive, or damaging, to marine calcifiers. These conditions make it more difficult for calcifying organisms to form shells or skeletons, perform metabolic functions, and survive.

Acidification trends in open-ocean surface waters tend to occur at a rate that is commensurate with the rate of the increase in atmospheric CO_2 (see, for example, trends of atmospheric CO_2 in comparison to surface ocean pCO_2 at the Hawai'i Ocean Time-series in Figure 16.3, this page). Acidification in coastal waters is more variable because of a combination of changes in circulation and upwelling, larger-amplitude seasonal signals in production and respiration than in the open ocean, and atmospheric CO_2 uptake (see Figure 16.4, p. 672; Feely et al., 2008, 2016, 2018; Chavez et al., 2017). In many coastal regions, pCO_2 rises more slowly than in the open ocean (see Section 16.4.1, p. 669; Laruelle et al., 2018). Along the North American Pacific Coast, climate-driven changes in upwelling circulation result in coastal acidification events. As mentioned in Section 16.4.1, upwelling-favorable winds along this coast have intensified over recent years, especially in the northern parts of the upwelling regimes (García-Reyes et al., 2015; McClatchie et al., 2016; Rykaczewski and Checkley 2008; Rykaczewski et al., 2015; Sydeman et al., 2014). Intensified upwelling supplies deep water to the shelf that is rich in DIC and nutrients but poor in oxygen. Ocean acidification and hypoxia thus are strongly linked ecosystem stressors because

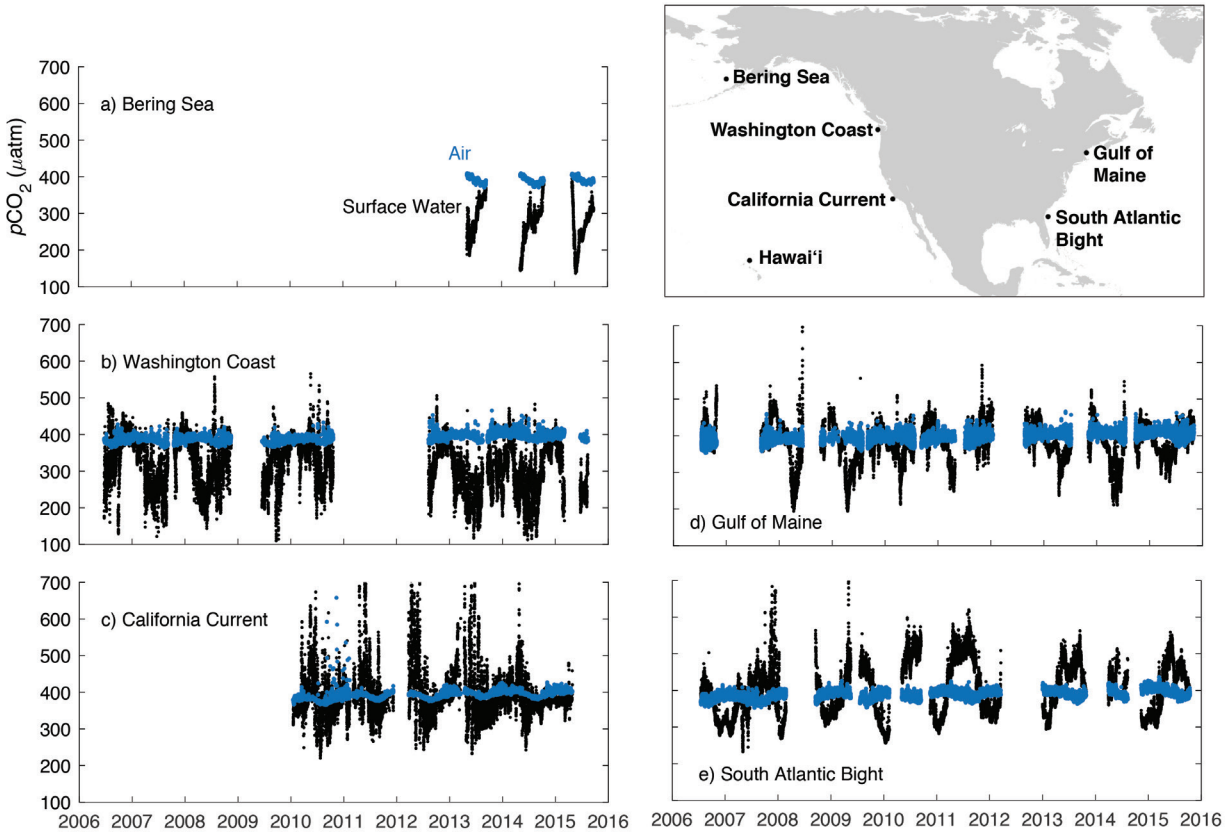

Figure 16.4. Partial Pressure of Carbon Dioxide (pCO_2) Data for the Surface Ocean (black) and Overlying Atmosphere (blue) at Five Coastal Sites. Data are in microatmospheres (μatm); map shows mooring locations. [Data sources: Bering Sea (mooring M2), Cross et al., 2014b. Washington coast (Cape Elizabeth mooring), Mathis et al., 2013. California Current (mooring CCE2), Sutton et al., 2012. Coastal Western Gulf of Maine mooring, Sutton et al., 2013. South Atlantic Bight (Gray's Reef mooring), Sutton et al., 2011.]

low-oxygen, high-CO_2 conditions derive from the microbial respiration of organic matter (Chan et al., 2016; Feely et al., 2008, 2016, 2018). In the northern California Current System, pCO_2, pH, and aragonite saturation reach levels known to be harmful to ecologically and economically important species during the summer upwelling season (see Ch. 17: Biogeochemical Effects of Rising Atmospheric Carbon Dioxide, p. 690; Barton et al., 2012, 2015; Bednaršek et al., 2014, 2016, 2017; Feely et al., 2008, 2016; Harris et al., 2013). In the Gulf of Alaska, aragonite saturation drops to near saturation values during the winter months when deep mixing occurs and surface ocean pCO_2 exceeds atmospheric pCO_2 (Evans and Mathis 2013). Along the Pacific Coast, 50% of shelf waters are projected to experience year-long undersaturation by 2050 (Gruber et al., 2012; Hauri et al., 2013; Turi et al., 2016).

Polar regions are naturally prone to acidification because of their low temperatures (Orr et al., 2005; Steinacher et al., 2009). In many Arctic coastal regions, pH and carbonate saturation state are naturally low relative to lower-latitude coastal settings. These low levels result from higher CO_2 solubility, the influence of multiple sources of freshwater (e.g., riverine, glacial melt, and sea ice melt) with varying CO_2 chemistries, and the high respiratory DIC content in bottom waters. The Beaufort and Chukchi Sea continental shelves experience inflows of naturally corrosive Pacific seawater with pH as low

as 7.6 (Mathis et al., 2011). The main contributing factor to the relatively high rates of acidification in polar waters is retreating sea ice, which adds meltwater from multiyear ice and increases the surface area of open water, thereby enhancing the uptake of atmospheric CO_2 (Cai et al., 2010b; Steiner et al., 2013). These factors, in combination with increasing atmospheric CO_2 levels, have set a faster pace of ocean acidification in the Arctic than projected trends in other coastal regions (Feely et al., 2009; Mathis et al., 2015a). Models predict annual average aragonite undersaturation (i.e., favoring dissolution) for the Bering Sea and the Chukchi Sea by 2070 and 2030, respectively (Mathis et al., 2015a). The Beaufort Sea upper halocline and deep waters now regularly show aragonite undersaturation (Mathis et al., 2015a; Miller et al., 2014). These chemical seawater signatures are propagated via M'Clure Strait and Amundsen Gulf into the CAA and beyond (Azetsu-Scott et al., 2010; Turk et al., 2016; Yamamoto-Kawai et al., 2013). Model projections based on the IPCC high-CO_2 emissions scenario, Representative Concentration Pathway 8.5 (RCP8.5), suggest the Beaufort Sea surface water will become undersaturated with respect to aragonite around 2025 (Steinacher et al., 2009; Steiner et al., 2014). As these conditions intensify, negative impacts on calcifying marine organisms are expected to become a critical issue, reshaping ecosystems and fisheries across the North American Arctic domain (Mathis et al., 2015b; Moore and Stabeno 2015).

In the northern GMx, surface aragonite saturation states typically range from 3.6 to 4.5 and are thus well above the dissolution threshold (Wang et al., 2013; Wanninkhof et al., 2015). Here excessive nutrient inputs from the Mississippi River result in hypoxia and eutrophication-induced acidification of near-bottom waters (Cai et al., 2011; Laurent et al., 2017). Similar to the California Current System, low-oxygen and high-CO_2 conditions coincide and derive from microbial respiration of organic matter (Cai et al., 2011; Laurent et al., 2017; Feely et al., 2018). Currently, aragonite saturation states are around 2 in hypoxic bottom waters and thus well above the saturation threshold. Projections suggest that aragonite saturation states of these near-bottom waters will drop below the saturation threshold near the end of this century (Cai et al., 2011; Laurent et al., 2018).

Recent studies indicate that the northern regions of the North American Atlantic Coast (the MAB and GOM) are more prone to acidification than the SAB (Wang et al., 2013; Wanninkhof et al., 2015). Coastal waters in this region have, on average, lower pH and lower aragonite saturation states than more southern coastal regions. These properties are driven primarily by a decrease in mean total alkalinity of shelf water from the SAB northward to the GOM. Seasonal undersaturation of aragonite in subsurface water is occurring in the GOM with photosynthesis and respiration playing a major role in controlling the seasonal variability of aragonite saturation states; dissolution of aragonite might already occur in fall and winter (Wang et al., 2017). With a significant shellfish industry, the GOM displays the lowest pH and aragonite saturation levels along the East Coast in summer (Wang et al., 2013).

16.5 Conclusions

The research community has made tremendous progress in improving understanding and constraining rates of carbon cycling in coastal waters since SOCCR1 (CCSP 2007), primarily because of a greatly expanded suite of observations, process studies, and models. However, quantification of many coastal carbon fluxes remains a significant challenge. Carbon is constantly exchanged across the air-sea interface as well as the interfaces between land and coastal ocean, coastal and open-ocean waters, and water and sediment. Net exchange fluxes and trends are relatively small signals masked by a large and fluctuating background. At present, most of these fluxes are not quantified well enough to derive well-constrained carbon budgets for North American coastal waters or to project how those fluxes will change in the future due to various drivers.

This chapter focused primarily on the role of ocean margins in sequestering atmospheric CO_2 and coastal ocean acidification. In the coastal ocean, a net removal of carbon from direct interaction with

the atmospheric reservoir can occur by export of dissolved or particulate carbon to the deep ocean or by permanent burial in sediments. Neither of these is easily observed or well quantified. The best-observed flux is gas exchange across the air-sea interface, although extracting the small net flux and its trend from a variable background remains a challenge. Ultimately, the removal of anthropogenic carbon is the relevant quantity for assessing the contribution of ocean margins to the uptake of anthropogenic carbon; however, the separation of anthropogenic fluxes from the natural background is thus far elusive for coastal waters.

Estimates of air-sea CO_2 fluxes currently provide the best evidence for the contribution of coastal waters to overall carbon uptake by the ocean. In the broad shelf system of the North American Atlantic Coast, shelf water is separated from the adjacent open ocean by persistent shelf break currents and density fronts. Available estimates suggest that the overall North American Atlantic Coast is a weak sink, with some subregions acting as sources (e.g., nearshore regions of the SAB), while others are either neutral (Scotian Shelf and GOM) or act as weak sinks (MAB and outer SAB). Large sections of the narrow shelf of the North American Pacific Coast are dominated by upwelling circulation, which leads to strong CO_2 outgassing near the coast. However, compensating for this outgassing is biologically driven uptake from upwelled nutrients further offshore. Recent estimates are consistent in suggesting that the region is a weak to moderate sink of atmospheric CO_2. The relatively wide shelves in the GMx are considered a weak net sink, with the West Florida Shelf and the western Gulf shelf acting as sources; the Mexico shelf being neutral; and only the northern shelf a clear sink that is driven largely by anthropogenic nutrient inputs from the Mississippi River. The wide, seasonally ice-covered shelves in the North American Arctic consistently are acting as a sink for atmospheric CO_2. The low surface-water pCO_2 in this region primarily results from low water temperatures and the decreased uptake of atmospheric CO_2 during a significant fraction of the year because of seasonal ice cover. Overall, North American coastal waters act as a sink, but regional variations and uncertainties are large.

Several drivers influence secular trends in coastal carbon fluxes and will continue to do so in the future. These drivers include rising atmospheric CO_2 levels, changes in atmosphere-ocean interactions (e.g., wind forcing and heat fluxes), changes in the hydrological cycle, and anthropogenic perturbations of global nutrient cycling (particularly, the nitrogen cycle). Coastal surface pCO_2 clearly does not closely track atmospheric pCO_2. Although there are a number of plausible mechanisms for potential future changes in coastal carbon uptake, the total effect cannot be predicted with any confidence. Regional model studies are beginning to address these challenges.

A major concern is coastal acidification, which can affect the growth, metabolism, and life cycles of many marine organisms, specifically calcifiers, and can trigger cascading ecosystem-scale effects. Most vulnerable are those organisms that precipitate aragonite, one of the more soluble forms of biogenic $CaCO_3$ in the ocean. Aragonite saturation states are routinely below saturation (i.e., favoring dissolution) in North American Arctic coastal waters. In the North American Pacific Coast region, atmospheric CO_2 uptake in combination with intensified upwelling that brings low-pH, low-oxygen water onto the shelves leads to aragonite levels below the saturation threshold in large portions of the subsurface waters. In the northern GMx, aragonite saturation states are well above the dissolution threshold. Although eutrophication-induced acidification occurs in bottom waters influenced by Mississippi River inputs of nutrients and freshwater, saturation levels remain well above the dissolution threshold.

Given the importance of coastal margins, both in contributing to carbon budgets and in the societal benefits they provide, further efforts to improve assessments of the carbon cycle in these regions are paramount. Critical needs are maintaining and expanding existing coastal observing programs, continuing national and international coordination and integration of observations, increasing development of modeling capabilities, and addressing stakeholder needs.

SUPPORTING EVIDENCE

KEY FINDING 1

Observing networks and high-resolution models are now available to construct coastal carbon budgets. Efforts have focused primarily on quantifying the net air-sea exchange of carbon dioxide (CO_2), but some studies have estimated other key fluxes, such as the exchange between shelves and the open ocean.

Description of evidence base

Observing networks are in place along the Atlantic, Pacific, and Arctic coasts of North America and the U.S. Gulf Coast (Alin et al., 2015; Bates et al., 2006, 2011; Cai et al., 2010a; Chen et al., 2013; Cross et al., 2014a; Dai et al., 2013; DeGrandpre et al., 2002; Evans et al., 2011, 2012, 2015b; Hales et al., 2005, 2012; Jiang et al., 2008; Mucci et al., 2010; Najjar et al., 2018; Robbins et al., 2009, 2014; Salisbury et al., 2008b, 2009; Shadwick et al., 2010, 2011; Vandemark et al., 2011; Wang et al., 2013, 2017).

Regional models are in place for the same regions (Cahill et al., 2016; Fennel et al., 2008; Fiechter et al., 2014; Pilcher et al., 2018; Previdi et al., 2009; Turi et al., 2014; Xue et al., 2016).

The emphasis on quantifying air-sea exchange is illustrated by the fact that the references listed in Table 16.1, p. 657, all provide an estimate of this flux, but few provide estimates of other fluxes. Few studies exist that do provide estimates of carbon exchange between shelves and open ocean; they include Fennel and Wilkin (2009), Barth et al. (2002), Hales et al. (2006), Xue et al. (2016), and Najjar et al. (2018).

Major uncertainties

This key message essentially contains statements of fact. Hence, this statement is not considered uncertain.

KEY FINDING 2

Available estimates of air-sea carbon fluxes, based on more than a decade of observations, indicate that the North American margins act as a net sink for atmospheric CO_2. This net uptake is driven primarily by fluxes in the high-latitude regions. The estimated magnitude of the net flux is 160 ± 80 teragrams of carbon per year (*medium confidence*) for the North American Exclusive Economic Zone, a number that is not well constrained.

Description of evidence base

This statement is supported by the numbers summarized in Tables 16.1, p. 657, and 16.2, p. 665. Consistent reports of outgassing exist only for the Gulf of Maine (GOM), where the net flux is almost neutral, and the West Florida Shelf. Contradictory reports exist for the Scotian Shelf. Everywhere else the net flux is reported as net uptake (i.e., sink), although with large uncertainties. Three independent studies also provide estimates of net air-sea CO_2 exchange in North American coastal waters. Two are global data syntheses (Chen et al., 2013; Laruelle et al., 2014), and one is from a process-based global model (Bourgeois et al., 2016; see Table 16.2, p. 665). The model of Bourgeois et al. (2016) estimates a net air-sea CO_2 flux of 160 teragrams of carbon

(Tg C) per year for the North American Exclusive Economic Zone (EEZ). The estimate is that the uncertainty is 50%.

These individual estimates cannot be combined because of discrepancies in numbers and gaps in coverage.

Major uncertainties

The consistency among studies pointing at North American coastal waters as a sink provides confidence, although each individual estimate is uncertain.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

The statement that North American coastal waters act as a sink overall can be made with high confidence and reflects the fact that studies are consistent in supporting this conclusion, even though each number itself comes with a large uncertainty. The overall uptake estimate is uncertain; hence, there is high confidence in stating that this flux estimate is poorly constrained.

Summary sentence or paragraph that integrates the above information

The consistency of many independent estimates reporting coastal uptake of atmospheric CO_2 builds confidence that these waters indeed act as a sink.

KEY FINDING 3

The increasing concentration of CO_2 in coastal and open-ocean waters leads to ocean acidification. Corrosive conditions in the subsurface occur regularly in Arctic coastal waters, which are naturally prone to low pH, and North Pacific coastal waters, where upwelling of deep, carbon-rich waters has intensified and, in combination with the uptake of anthropogenic carbon, leads to low seawater pH and aragonite saturation states in spring, summer, and early fall (*very high confidence, very likely*).

Description of evidence base

In Arctic coastal waters, pH and carbonate saturation state are naturally low (Cai et al., 2010b; Mathis et al., 2011; Steiner et al., 2013). The pace of ocean acidification is faster in the Arctic than in other coastal and open-ocean regions (Fabry et al., 2009; Feely et al., 2009; Mathis et al., 2015a). The Beaufort Sea upper halocline and deep waters now regularly show aragonite undersaturation (Mathis et al., 2015a; Miller et al., 2014). These chemical seawater signatures are propagated via M'Clure Strait and Amundsen Gulf into the Canadian Archipelago and beyond (Azetsu-Scott et al., 2010; Turk et al., 2016; Yamamoto-Kawai et al., 2013). Variability in the carbon content of freshwater end members also has been shown to contribute to undersaturation events in coastal waters of the Gulf of Alaska region (Siedlecki et al., 2017; Evans et al., 2014)

In the North America Pacific Coast (NAPC) region, anthropogenic CO_2 uptake combined with climate-driven changes in upwelling circulation result in coastal acidification events. Upwelling-favorable winds along the NAPC have intensified over recent years, especially in the northern parts of the upwelling regimes (García-Reyes et al., 2015; McClatchie et al., 2016; Rykaczewski and Checkley 2008; Rykaczewski et al., 2015; Sydeman et al., 2014). In the northern California Current System, pCO_2 (partial pressure of CO_2), pH, and aragonite saturation

reach levels known to be harmful to ecologically and economically important species during the summer upwelling season (see Ch. 17: Biogeochemical Effects of Rising Atmospheric Carbon Dioxide, p. 690; Barton et al., 2012, 2015; Bednaršek et al., 2014, 2016, 2017; Feely et al., 2008, 2016, 2018; Harris et al., 2013; Siedlecki et al., 2016).

Major uncertainties

Statement is well supported by the literature. No major uncertainties.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Statement is well supported by the literature. No major uncertainties.

Estimated likelihood of impact or consequence, including short description of basis of estimate

Corrosive waters have been observed in the Arctic and North Pacific coastal regions (Feely et al., 2008, 2016; Mathis et al., 2015a; Miller et al., 2014). A more comprehensive list of references is given in the description above and in the chapter body.

Summary sentence or paragraph that integrates the above information

Statement that corrosive waters regularly occur is well supported by the literature because these conditions have been directly observed. There are no major uncertainties.

KEY FINDING 4

Expanded monitoring, more complete syntheses of available observations, and extension of existing model capabilities are required to provide more reliable coastal carbon budgets, projections of future states of the coastal ocean, and quantification of anthropogenic carbon contributions.

Description of evidence base

The underlying motivation for constructing complete carbon budgets for coastal waters is that permanent burial of carbon in coastal sediments and export of carbon from coastal waters to the deep ocean both remove anthropogenic carbon from the atmospheric reservoir. The relevant carbon flux in this context is the burial or export of anthropogenic carbon, not total burial or export. Only total fluxes can be observed directly. Distinction between anthropogenic fluxes and the natural background has not been attempted in regional observational or modeling studies, because more comprehensive accounting than is available for carbon fluxes and improved modeling capabilities would be needed. The study by Bourgeois et al. (2016) is the first to estimate coastal anthropogenic carbon uptake in a global model. The estimated net air-sea exchange of CO_2 from this global model is reported for a regional decomposition of the EEZs of the United States, Canada, and Mexico in Table 16.3, p. 666. The model simulates a net uptake of CO_2 in North American coastal waters that is of similar magnitude to estimates of organic carbon burial and riverine carbon input, but the latter two numbers are uncertain because they are each taken from one individual study and not corroborated by multiple references. However, the similar magnitudes of these numbers illustrate that current coastal carbon budgets are uncertain and that constraining just the air-sea gas exchange will not be sufficient to quantify the export of anthropogenic carbon by coastal processes.

Major uncertainties

This report's synthesis of the current literature shows that the magnitudes of several significant components of coastal carbon budgets are currently uncertain.

Summary sentence or paragraph that integrates the above information

The synthesis in this chapter shows that coastal carbon budgets and anthropogenic contributions to the underlying fluxes are currently uncertain. Thus, more observations and modeling efforts could reduce these uncertainties.

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Section IV

CONSEQUENCES AND WAYS FORWARD

These chapters outline future projections of rising atmospheric carbon and its associated consequences. They detail how science can inform decision making at the federal, provincial, state, tribal, and local levels across North America, and how those decisions could affect the carbon cycle in the future.

Chapter 17
Biogeochemical Effects of Rising Atmospheric Carbon Dioxide

Chapter 18
Carbon Cycle Science in Support of Decision Making

Chapter 19
Future of the North American Carbon Cycle

17 Biogeochemical Effects of Rising Atmospheric Carbon Dioxide

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KEY FINDINGS

1. Rising carbon dioxide (CO_2) has decreased seawater pH at long-term observing stations around the world, including in the open ocean north of Oahu, Hawai'i; near Alaska's Aleutian Islands; on the Gulf of Maine shore; and on Gray's Reef in the southeastern United States. This ocean acidification process has already affected some marine species and altered fundamental ecosystem processes, and further effects are likely (*high confidence, likely*).

2. While atmospheric CO_2 rises at approximately the same rate all over the globe, its non-climate effects on land vary depending on climate and dominant species. In terrestrial ecosystems, rising atmospheric CO_2 concentrations are expected to increase plant photosynthesis, growth, and water-use efficiency, though these effects are reduced when nutrients, drought, or other factors limit plant growth (*very high confidence, very likely*). Rising CO_2 would likely change carbon storage and influence terrestrial hydrology and biogeochemical cycling, but concomitant effects on vegetation composition and nutrient feedbacks are challenging to predict, making decadal forecasts uncertain.

3. Consequences of rising atmospheric CO_2 are expected to include difficult-to-predict changes in the ecosystem services that terrestrial and oceanic systems provide to humans. For instance, ocean acidification resulting from rising CO_2 has decreased the supply of larvae that sustains commercial shellfish production in the northwestern United States. In addition, CO_2 fertilization (increases) plus warming (decreases) are changing terrestrial crop yields (*high confidence, likely*).

4. Continued persistence of uptake of carbon by the land and ocean is uncertain. Climate and environmental changes create complex feedbacks to the carbon cycle; how these feedbacks modulate future effects of rising CO_2 on carbon sinks is unclear. There are several mechanisms that would reduce the ability of land and ocean sinks to continue taking up a large proportion of rising CO_2 (*very high confidence*).

Note: Confidence levels are provided as appropriate for quantitative, but not qualitative, Key Findings and statements.

17.1 Introduction

The most central planetary outcome of rising atmospheric carbon dioxide (CO_2), methane (CH_4), and black carbon is their warming effect on Earth's atmosphere, which influences weather and climate (IPCC 2013). The *Climate Science Special Report* (CSSR; USGCRP 2017) concludes with high confidence that Earth's observed temperature increase in the last century results from human influence, especially from emissions of greenhouse gases including CO_2 and CH_4 and particulates such as black carbon. Furthermore, CSSR (USGCRP 2017) demonstrates that the consequences of atmospheric warming are profound and diverse, significantly altering planetary surface temperatures and overall climate and thus also directly or indirectly altering countless oceanic and terrestrial processes.

Increased global temperatures lead to extremes in temperature and precipitation (IPCC 2013), causing heatwaves, droughts, floods, and changing storm system patterns (Melillo et al., 2014), with additional consequences for the carbon cycle. For instance, warming and changing weather melt polar ice cover and thaw Arctic permafrost, releasing CH_4 and CO_2 as stored organic matter is microbially respired (see Ch. 11: Arctic and Boreal Carbon, p. 428). Melting glaciers and seawater expansion will raise sea levels, changing ecosystem boundaries and affecting net carbon fluxes (IPCC 2013; USGCRP 2017). Heating and ice melt will stratify the ocean, dampening the ability of vertical mixing to refresh surface waters with nutrients that support primary production (IPCC 2013). A warmer ocean will hold less carbon, because warmer ocean temperatures decrease the solubility of CO_2 in seawater (Zeebe and Wolf-Gladrow 2001). Both long-term increases in ocean temperature and short-term marine heatwaves may affect stocks of organic and inorganic carbon

contained in marine ecosystems and sediments (see Ch. 16: Coastal Ocean and Continental Shelves, p. 649). Changing snowpack dynamics will affect water availability significantly in riverine ecosystems. In midlatitudes, fire frequency and severity will change as a result of changes in temperature and precipitation. These shifts and feedbacks are very likely to have widespread, interacting effects on human and natural systems that elicit a variety of responses.

Upon this backdrop of accumulating, thermally driven planetary climate change that impacts the carbon cycle, rising atmospheric CO_2 is also affecting oceanic and terrestrial systems in nonthermal ways that have only begun to be understood since the *First State of the Carbon Cycle Report* (SOCCR1; CCSP 2007). The observed rise in atmospheric CO_2 since the 1950s is lower than the contributions from estimated emissions because both the ocean and land continue to take up a portion of the atmospheric CO_2 from anthropogenic (i.e., human) activities, indicating both systems are carbon sinks (Ballantyne et al., 2012). Ocean uptake prevents some degree of atmospheric warming but results in ocean acidification (see Ch. 16: Coastal Ocean and Continental Shelves), which drives a host of chemical and biological impacts, as reviewed below. The terrestrial "CO_2 fertilization effect" is the increased uptake of CO_2 per unit land area caused by rising CO_2, which is greater than could be expected from plant regrowth after land-use change and stimulation by increased nutrient availability. Global analysis suggests that CO_2 fertilization is responsible for up to 60% of the overall land sink (Schimel et al., 2015), but persistence of these benefits into the future is highly uncertain (Müller et al., 2014; Smith et al., 2016). Moreover, the thermal impacts of climate change will interact with, enhance, or in some cases overwhelm the nonthermal effects of rising atmospheric CO_2 on ecosystems; these different future scenarios are explored elsewhere in this report (see Ch. 19: Future of the North American Carbon Cycle, p. 760). These findings have important implications; the current partitioning of anthropogenic CO_2 sinks among the ocean, atmosphere, and terrestrial biosphere, therefore, also will change in the future. Because CO_2 is involved in all aspects of growth in biological systems there also are important non-climate effects of increased atmospheric CO_2 concentration.

To better explain the non-climate effects of rising CO_2 on ecological systems, this chapter first reviews the historical context of rising CO_2 and then examines its impact on ocean and terrestrial systems (see Figure 17.1, p. 693), including ocean acidification, productivity and ecosystem changes, interactions with other environmental changes, and carbon cycle feedbacks. Also examined are changes in ecosystem services (or benefits to humans) resulting from chemical changes in Earth system processes and how those intersect with thermally driven changes. This examination is followed by a review of outstanding research needs for gaining greater clarity on the effects of rising CO_2 on oceanic and terrestrial systems.

Such a comprehensive, collected examination of the effects of carbon cycle changes is new in the *Second State of the Carbon Cycle Report* (SOCCR2) and responds to the requirement in the Global Change Research Act that "analyzes the effect of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity" (Global Change Research Act 1990, Section 106). Since publication of SOCCR1 (CCSP 2007), many highly influential reports have assessed the consequences of carbon cycle changes on Earth systems, including the *Third National Climate Assessment* (Melillo et al., 2014), the *Intergovernmental Panel on Climate Change Fifth Assessment Report* (IPCC AR5; IPCC 2013), and the CSSR (USGCRP 2017). This chapter updates the conclusions of the reports cited above, with the most recent literature and with particular attention to North America. Those reports treat the direct and indirect effects of increasing CO_2 in greater detail than does this chapter, which focuses to a greater extent on the direct and non-climatic effects of increased atmospheric CO_2 concentrations.

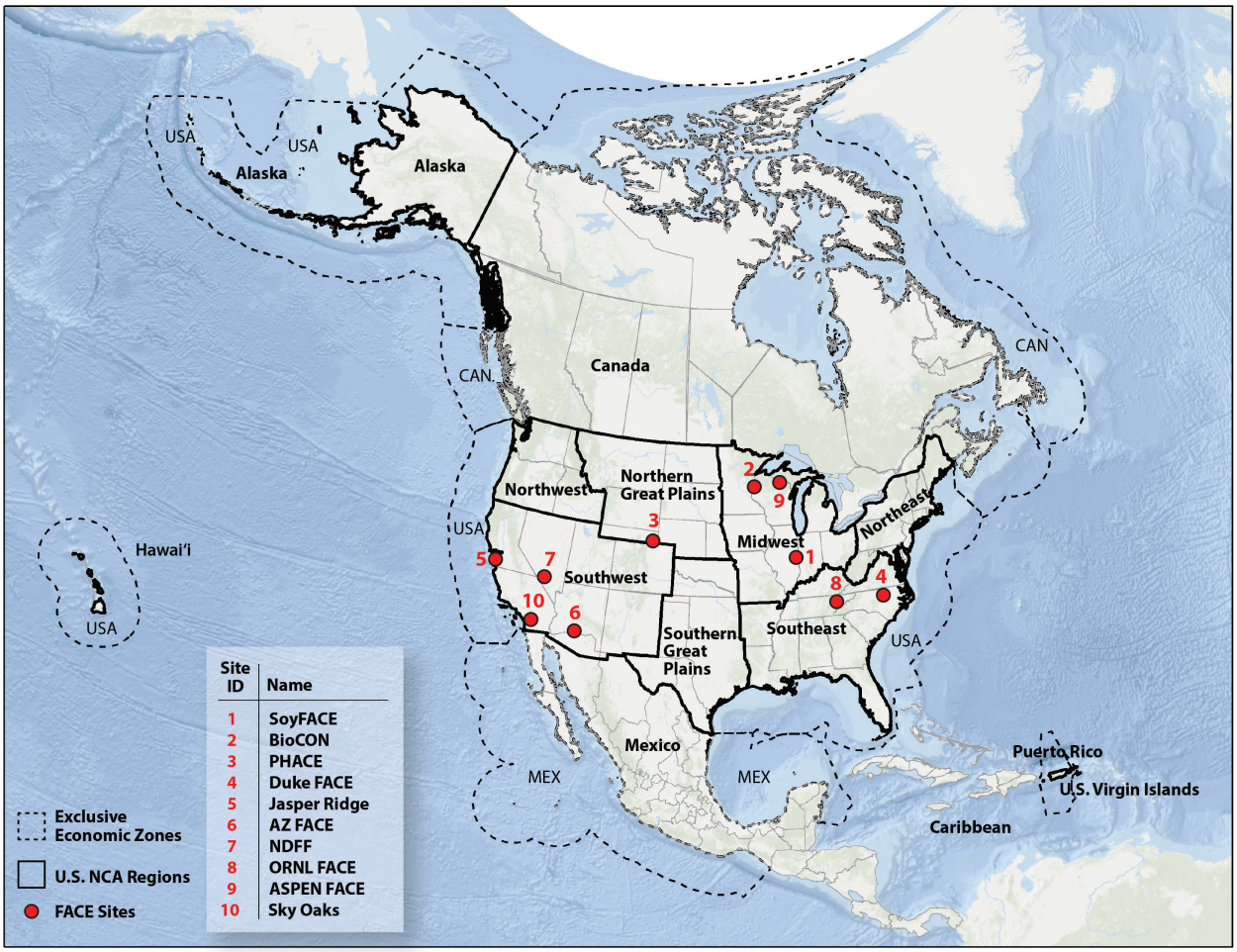

Figure 17.1. Study Sites Examining Terrestrial Ecosystem Responses to Elevated Carbon Dioxide (CO_2). Projects include **1)** Soybean Free Air Concentration Enrichment (SoyFACE); **2)** Biodiversity, CO_2, and Nitrogen (BioCON); **3)** Prairie Heating and CO_2 Enrichment (PHACE); **4)** Duke Forest Free-Air CO_2 Enrichment (FACE) Experiment; **5)** Jasper Ridge Global Change Experiment; **6)** Maricopa, Ariz., FACE experiments; **7)** Nevada Desert FACE Facility (NDFF); **8)** Oak Ridge National Laboratory (ORNL) FACE; **9)** Aspen FACE Experiment; and **10)** Sky Oaks Long-term Carbon Flux Measurements. [Figure source: Christopher DeRolph, Oak Ridge National Laboratory.]

17.2 Atmospheric CO_2 in Prior Geological Ages

Over geological time (i.e., the last 500 million years), atmospheric CO_2 levels have at times been well in excess of current CO_2 concentrations (see Figure 17.2, p. 694). However, human civilization developed during the last 10,000 years, a time when atmospheric CO_2 was never higher than it is today (Augustin et al., 2004). Once humans began extensively altering the landscape and burning fossil fuels, atmospheric CO_2 and CH_4 began to rise rapidly and drive changes in atmospheric, terrestrial, and oceanic systems and processes (Olofsson and Hickler 2007).

Changes in atmospheric CO_2 changed Earth's climate and ocean pH and altered the course of plant evolution. Atmospheric CO_2 was likely higher than 5,000 parts per million (ppm) at times during the last 540 million years (Phanerozoic Eon) and declined to current levels during the last 25 million years (Doney and Schimel 2007; Royer 2006; see

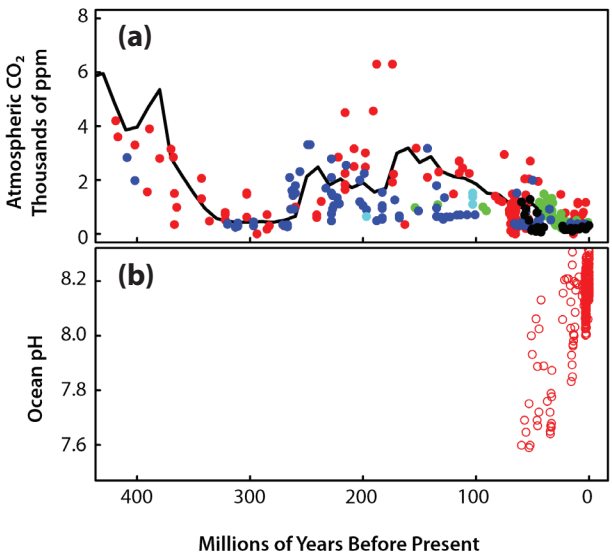

Figure 17.2. Geological Context of Carbon Dioxide (CO_2). (a) Paleoreconstruction of atmospheric CO_2 in parts per million (ppm) versus time over the past 400 million years. The Geologic Carbon Cycle (GEOCARB) Model simulation is depicted by the black line; also shown (as dots) are publicly archived proxy data for paleosol carbon isotopes (red), phytoplankton carbon isotopes (green), stomatal indices (blue), marine boron isotopes (black), and liverwort carbon isotopes (cyan). **(b)** Ocean surface pH, shown in red, has increased over the last 50 million years as atmospheric CO_2 declined. [Data sources: Panel (a) from Royer 2006. Data are publicly available at www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/climate-forcing. Panel (b) proxy data from Hönisch et al., 2012.]

Figure 17.2, this page). During this eon, periods of frequent glaciation events in Earth's history are associated with CO_2 concentrations below 1,000 ppm (Royer 2006). A strong decline of atmospheric CO_2 during the Carboniferous Period (359 million years ago) is associated with the proliferation of land plants. Extensive burial of plants from this period resulted in the massive deposits of fossil fuels now being mined. Declining atmospheric CO_2 concentrations at the Eocene-Oligocene boundary (34 million years ago) induced dynamic ice sheet formation over Antarctica and ultimately led to substantial cooling of global climate over the subsequent 10 million years (DeConto and Pollard 2003). During the Quaternary Period (last 1 million years), ice core records show that temperature increases of ~3°C were associated with CO_2 increases of ~100 ppm (Petit et al., 1999). Recent analyses show that during the last deglaciation (from ~21,500 to ~11,500 years ago), observed increases in global temperature lagged behind observed increases in atmospheric CO_2 (Shakun et al., 2012). The glacial-interglacial cycle in Earth's climate during the Quaternary period is caused by a combination of changes in Earth's orbit, atmospheric greenhouse gases, and ocean circulation (Rohling et al., 2018).

The evolution of different ways of performing photosynthesis has a strong influence on the non-climate consequences of rising CO_2 on land. Fundamental to plant life on Earth, atmospheric CO_2 concentrations and their dynamics over geological time have played an important role in the evolution of photosynthesis and the distribution of different vegetation types (Beerling et al., 2001; Monson and Collatz 2011). RUBISCO (ribulose-1, 5-bisphosphate carboxylase-oxygenase), the enzyme that catalyzes the transfer of atmospheric CO_2 into plant sugars and biomass, evolved in early algae during a time of high CO_2 at least 2.8 billion years ago (Doney and Schimel 2007), though perhaps much earlier (Allwood et al., 2006; Raven et al., 2012). Plants evolved different photosynthetic mechanisms and anatomies in response to the relatively low CO_2 concentrations that persisted from about 300 million years ago, an environment which enabled C_4 grasses (e.g., ancestors of maize, sugarcane, and sorghum) and the cactus family to dominate arid portions of the Earth because of their greater water-use efficiency and drought tolerance (Berner 1997; Osborne and Sack 2012; Pagani et al., 2005).

Prior geological eras also provide information about potential impacts of high atmospheric CO_2 on ocean chemistry (Hönisch et al., 2012). Atmospheric CO_2 dissolves in seawater and creates carbonic acid, which lowers pH and decreases the concentration of carbonate ions present in solution. The closest analogs to present conditions may be the Paleocene-Eocene Thermal Maximum

(56 million years ago), Triassic-Jurassic mass extinction (~200 million years ago), and Permo-Triassic mass extinction (252.3 million years ago; Hönisch et al., 2012). All these events are associated with evidence of detrimental impacts on calcifying organisms including, in some instances, their extinction. However, definitively attributing negative effects on calcifiers to acidification is not possible because of other factors (e.g., ocean circulation, warming, oxygenation, and asteroid impacts) that may have co-occurred or contributed to the decline or demise of these organisms. Moreover, geochemical proxies indicating pH or ocean carbonate chemistry conditions, particularly for times before the Cretaceous Period (>65 million years ago), are limited and have large uncertainties.

Since the start of the Industrial Revolution, anthropogenic emissions have resulted in increased atmospheric CO_2 concentrations detectable by changes in the ratio of ^{13}C and ^{12}C isotopes in the biosphere (Keeling 1979; Suess 1955). Fossil fuels have less of the ^{13}C isotope because they are composed of dead plants and animals, and burning them changes the isotope ratio in the atmosphere. Isotopic studies indicate some of the carbon released from fossil sources becomes incorporated into all organisms, including those as diverse as trees (Suess 1955), marine fish (Fraile et al., 2016), and penguins (Hilton et al., 2006). The decrease in ocean pH since the start of the Industrial Revolution matches or exceeds the pH levels observed for the Quaternary glacial-interglacial period (Pelejero et al., 2010; Turley et al., 2006). Moreover, projected changes in ocean pH by 2100 well exceed those that occurred during the preindustrial period (Bijma et al., 2013; Turley et al., 2006). Recent global changes in upper ocean chemistry likely are occurring more rapidly than at any time over the past 300 million years (Doney et al., 2014; Hönisch et al., 2012). The rates and magnitude of change may soon move the ocean ecosystem into "uncharted territory," with conditions unlike any that contemporary marine life have faced during their recent evolutionary history (Gattuso et al., 2015; Turley et al., 2006).

17.3 Aquatic Consequences of Rising CO_2

17.3.1 Ocean Acidification

Increased uptake of CO_2 by the ocean from the beginning of the Industrial Revolution has led to decreased seawater pH and a lower calcium carbonate ($CaCO_3$) mineral saturation state (see Ch. 16: Coastal Ocean and Continental Shelves, Section 16.4.2, p. 670). Average pH values for open-ocean surface water have decreased by approximately 0.11 units from a preindustrial mean value of 8.17, equivalent to an increase of about 28% in hydrogen ion concentration (Feely et al., 2004, 2009; Gattuso et al., 2015; Orr et al., 2005). As a result of ocean acidification, the oceanic average concentration of carbonate ion (CO_3^{2-}) has declined about 16% from preindustrial values (Bopp et al., 2013; Doney et al., 2009; Gattuso et al., 2015). These changes in carbonate chemistry caused by rising atmospheric CO_2 have a variety of effects on aquatic life (e.g., Orr et al., 2005 and Kroeker et al., 2013), which is now an area of active research. Thirty-year ocean time-series datasets (e.g., Bates et al., 2014; Dore et al., 2009) provide direct evidence of this phenomenon worldwide (see Figure 17.3, p. 696). By the end of this century, surface ocean pH is expected to decline by another 0.1 to 0.4 units, and CO_3^{2-} concentration is expected to decline by as much as 50% compared to preindustrial conditions (see Figure 17.4, p. 697).

Significant changes in ocean acidity are readily apparent in the subtropical open ocean (see Figure 17.3, p. 696) and in several coastal locations (Sutton et al., 2016). High-quality, long-term datasets in extremely nearshore locations are limited, but ocean acidification has been documented year-round at time-series observatories near Alaska's Aleutian Islands and Oahu, Hawai'i (both open-ocean sites), and the Gulf of Maine and Gray's Reef off Georgia (both coastal ocean sites; Sutton et al., 2016). Conditions are more variable at coastal and nearshore time-series sites in the California Current and off Washington state (see Ch. 16: Coastal Ocean and Continental Shelves, Section 16.4.2), but they still confirm the presence of significantly

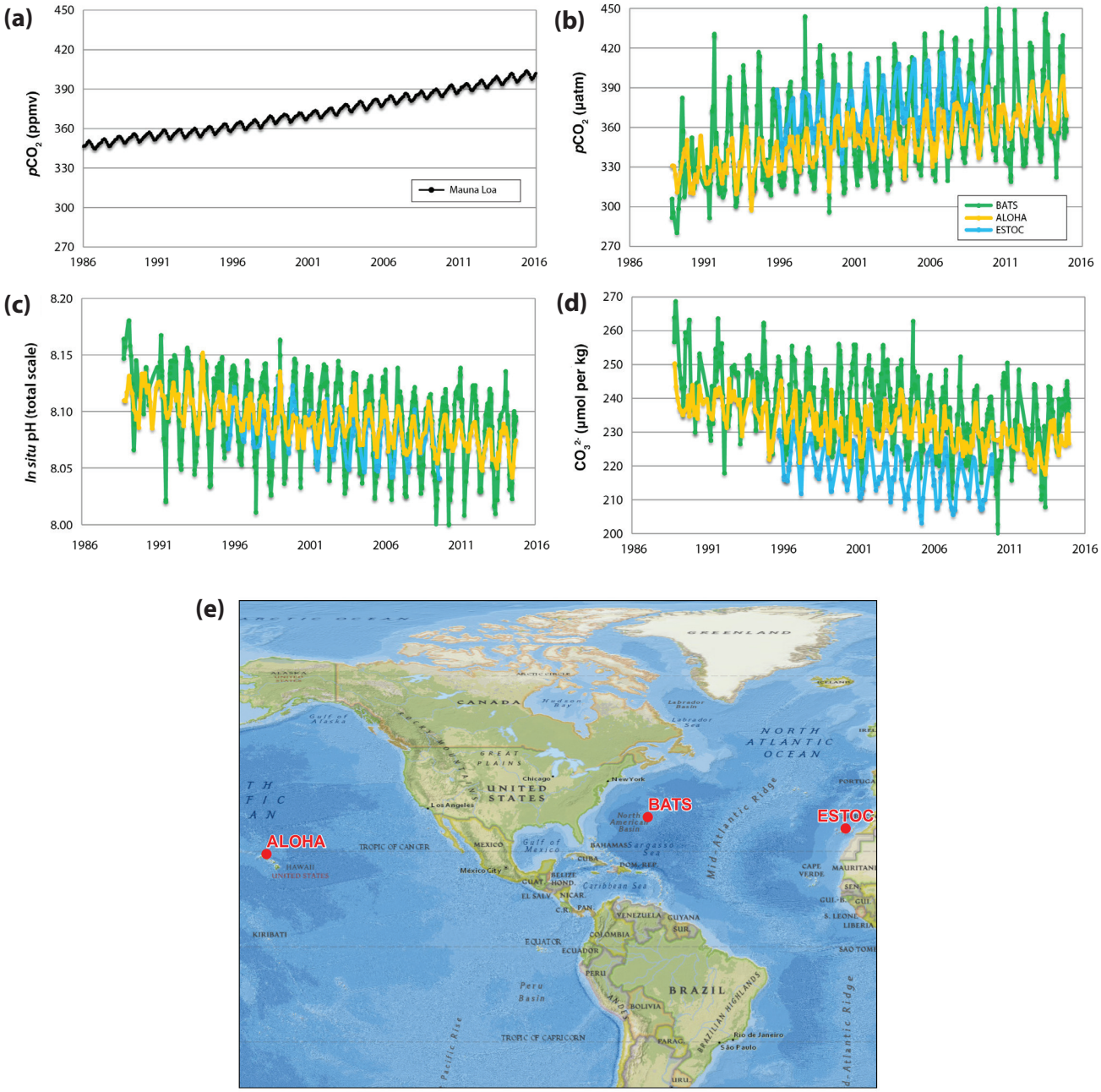

Figure 17.3. Evidence for Ocean Acidification from Ocean Time-Series Stations. (a) Mauna Loa, Hawai'i; atmospheric carbon dioxide (CO_2) in parts per million by volume (ppmv) versus time. **(b)** Surface ocean partial pressure of CO_2 (pCO_2) in microatmospheres (µatm) versus time for three ocean time-series monitoring stations: Bermuda Atlantic Time-series Study (BATS), A Long-Term Oligotrophic Habitat Assessment (ALOHA), and European Station for Time series in the Ocean at the Canary Islands (ESTOC). **(c)** Surface ocean pH versus time for BATS, ALOHA, and ESTOC. **(d)** Carbonate ion (CO_3^{2-}) versus time for BATS, ALOHA, and ESTOC. **(e)** Map of BATS, ALOHA, and ESTOC monitoring station locations. [Figure sources: Panel (a) from Scripps Institution of Oceanography, NOAA Earth System Research Laboratory. Panels (b–d) adapted from Fig. 3.18 (updated with new time-series data) from Rhein et al., 2013; Copyright IPCC, used with permission. Panel (e) from Christopher DeRolph, Oak Ridge National Laboratory.]

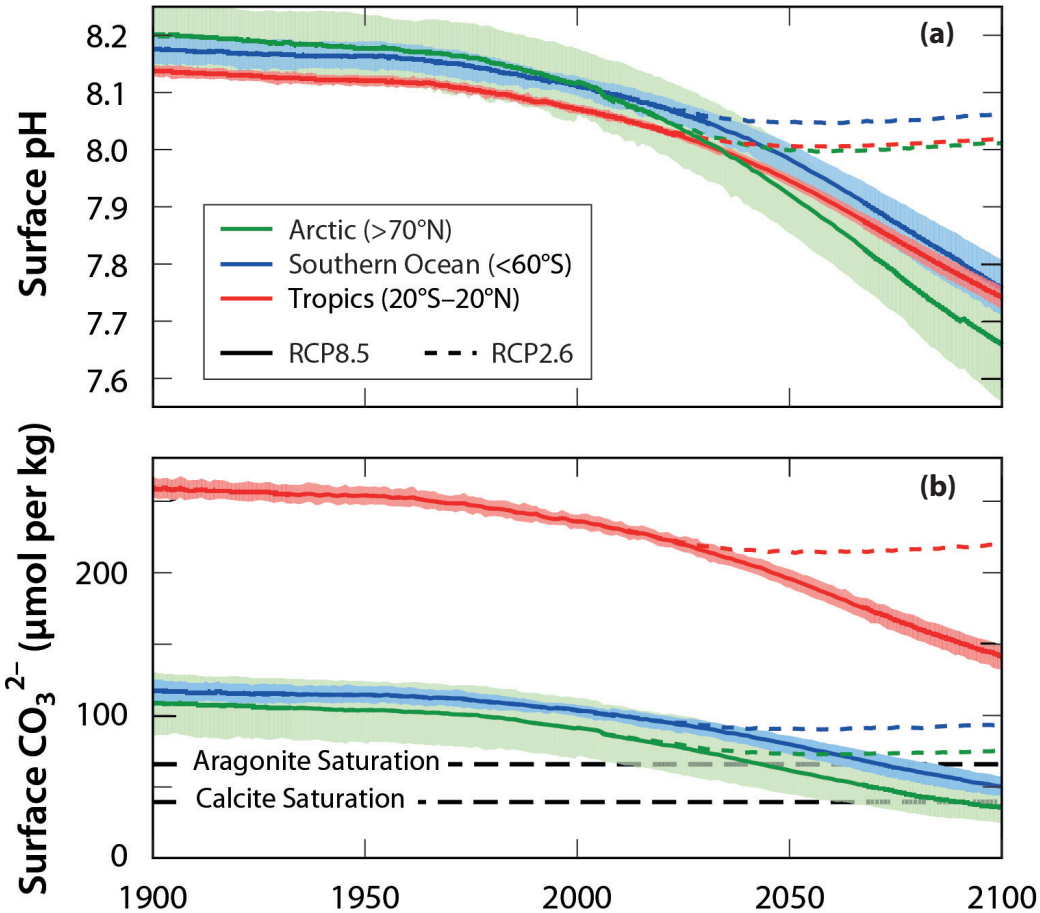

Figure 17.4. Regional Differences in Acidification Projections. Changes in **(a)** surface ocean pH and **(b)** surface carbonate ion (CO_3^{2-}) concentration (in micromoles per kg) through time for three ocean locations for the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathway (RCP)8.5 and 2.6 scenarios based on the Coupled Model Intercomparison Project Phase 5 (CMIP5) analysis. See Ch. 19: Future of the North American Carbon Cycle, p. 760, for RCP explanations. [Figure source: Adapted from Figs. 6.28(a) and 6.29(a) from Ciais et al., 2013; Copyright IPCC, used with permission.]

acidified conditions during some portions of every year (Sutton et al., 2016). The pH values in coastal waters are much more variable than those in the open ocean (Friedrich et al., 2012; Hofmann et al., 2010; Johnson et al., 2013; Sutton et al., 2016) because of natural processes such as upwelling, biological consumption and release of CO_2, temperature- and salinity-driven solubility changes in CO_2, or local human inputs of acid-producing substances (see Ch. 16: Coastal Ocean and Continental Shelves, Section 16.4.2, p. 670). Variable coastal processes make long-term pH trends somewhat harder to discern (Sutton et al., 2016), but these processes can enhance acidification (Doney 2010; Feely et al., 2008; Kelly et al., 2011) far beyond global average projections. The projected long-term average global increase in acidity (decreasing pH values) in the next 20 to 40 years due to atmospheric CO_2 (see Figure 17.4, this page) is much greater than the natural variability of pH values observed since monitoring began, underscoring the idea that marine life will face unfamiliar seawater chemistry conditions in the near future.

Many coastal margins also suffer from excess anthropogenic nitrogen and phosphorus inputs, which cause algal overgrowth (eutrophication) and, in some cases, increased microbial digestion (remineralization) of organic matter in bottom waters (see Ch. 16: Coastal Ocean and Continental Shelves, p. 649). These processes further increase CO_2 in water, reduce oxygen (i.e., deoxygenation) and pH, and decrease $CaCO_3$ mineral saturation (Cai et al., 2011; Diaz and Rosenberg 2008; Feely et al., 2016; Rabalais et al., 2002). Multiple stresses to coastal zones (e.g., warming, ocean acidification, and deoxygenation) can cause compounding harm to marine ecosystem health (Bijma et al., 2013; Wallace et al., 2014), complicating detection of individual organism impacts and ecosystem trends from acidification (Duarte et al., 2013; Harvey et al., 2013). Future research about how to manage aquatic ecosystems under global change needs to account for the complexity of climate and non-climate drivers and responses in both coastal and ocean environments (Blackford 2010; Riebesell and Gattuso 2015).

17.3.2 Acidification of Freshwater

Inland freshwater can dissolve excess atmospheric CO_2 just as seawater does. However, the dearth of long-term, high-precision, high-accuracy carbonate chemistry datasets for even major freshwater bodies like the Laurentian Great Lakes precludes attributing a discernible acidification trend in freshwater bodies to atmospheric CO_2 (Phillips et al., 2015). As in coastal waters, local processes also can significantly alter freshwater pH, complicating detection and attribution of changes driven by atmospheric CO_2 in lakes and rivers. The effects of acidification-driven changes due to increasing atmospheric CO_2 on lake ecosystems have not been determined (Hasler et al., 2015), but species-level studies suggest that, just as in ocean environments, impacts to freshwater organisms could be widespread and yet difficult to forecast (Weiss et al., 2018).

17.3.3 Changes in Ocean Biology and Ocean Biological Processes

Investigations of ocean acidification's effect on marine life show evidence of a wide range of sensitivities within and across diverse groups of organisms. Calcifying phytoplankton like coccolithophorids as well as multicellular organisms like scleractinian corals, pteropods, foraminifera, bivalves, crustaceans, and gastropods generally show negative but complex responses to ocean acidification, including altered biological processes such as growth, photosynthesis, calcification, and reproductive success (Bednaršek et al., 2016; Hofmann et al., 2010; Kroeker et al., 2013; Riebesell and Tortell 2011; Meyer and Riebesell 2015). Several finfish and shark species display altered risk-taking and hunting behaviors (Hamilton et al., 2014; Munday et al., 2014; Dixson et al., 2014), responses which have been related to changes in olfaction and neurotransmitter levels that result from ocean acidification (Munday et al., 2009; Dixson et al., 2010). Developmental changes in some harvested species such as summer flounder and tuna have also been noted (Chambers et al., 2014; Frommel et al., 2016). Conversely, photosynthesis of phytoplankton (algae), seagrasses, and kelp generally increases (Fu et al., 2007; Hutchins et al., 2013; Riebesell et al., 2007; Mackey et al., 2015), although net responses are highly species-specific and limited by several cellular processes, including species' carbon capture mechanisms (Mackey et al., 2015). Species responsible for harmful algal blooms are stimulated by changing ocean temperatures, carbonate chemistry, and nutrient ratios, displaying higher growth rates and greater toxin production (Fu et al., 2012). Theory suggests that acidification also may affect bioavailability of nutrients and trace minerals and stoichiometry of biogeochemical processes (Millero et al., 2009), but experimental results are mixed (Breitbarth et al., 2010; Shi et al., 2010). Co-occurrence of elevated temperatures, excessive nutrient inputs, changes in light availability, and increased hypoxia are likely to exacerbate and complicate the effects of ocean acidification on marine organisms or ecosystems (Bijma et al., 2013; Kroeker et al., 2013).

Ocean acidification impacts at the ecosystem level are difficult to predict because of the complexity of species- and population-level responses, but that research is beginning. Population-scale projections

of ocean acidification's effects have been developed for a few high-value, intensively managed single-species fisheries, including Tanner crab (Punt et al., 2016) and sea scallop (Cooley et al., 2015). More broadly, physiological and behavioral changes could alter predator-prey relationships and other species interactions, driving changes in species abundance and composition of ecological communities. Ocean acidification contributes to net loss of corals, and this loss destroys reef habitats and displaces associated marine communities (Hoegh-Guldberg et al., 2007). Ecosystem-scale projections incorporating ocean acidification and other environmental changes are only now being developed for select locations (e.g., California Current, Puget Sound, and northeastern United States; Busch et al., 2013; Fay et al., 2017; Kaplan et al., 2010). Much of the complexity in observed responses lies in 1) different timescales of response relative to the change in ocean acidification, 2) organisms' abilities to acclimate or genetically adapt, and 3) linkages between ocean acidification and other environmental stressors. Observational (Pespeni et al., 2013; Wootton et al., 2008), integrative (Boyd et al., 2014), and modeling (e.g., Dutkiewicz et al., 2015) studies emphasize the complexity of observed and predicted changes and suggest that future community and functional responses are likely to be more profound than the changes already observed.

17.3.4 Limits in Ocean CO_2 Uptake Capacity

Acidification varies with latitude because CO_2 solubility depends on temperature, with lower-temperature waters capable of holding more CO_2 and thus becoming more readily acidified. Models show that the suite of ocean changes (e.g., circulation, biological productivity, and ventilation) associated with atmospheric CO_2 absorption and the thermal effects of CO_2 and other greenhouse gases on the ocean are likely to decrease the ocean's future ability to take up atmospheric CO_2 (see Ch. 19: Future of the North American Carbon Cycle, Section 19.6, p. 779). In the near future, polar ecosystems may change enough to become *undersaturated* with respect to $CaCO_3$ minerals (Feely et al., 2009; Orr et al., 2005; Steinacher et al., 2010), owing to the large amount of CO_2 already dissolved in high-latitude ocean areas. When waters are undersaturated, $CaCO_3$ minerals will not precipitate. Even though low-latitude ocean areas will not become undersaturated with $CaCO_3$ minerals in the future, pH conditions will exceed or have already exceeded the bounds of observed natural variability (see Figure 17.4, p. 697; Sutton et al., 2016), exposing low-latitude organisms such as warm-swater coral reefs to chemical conditions suboptimal for growth and calcification (Fabricius et al., 2011).

17.4 Terrestrial Consequences of Rising CO_2

The CO_2 fertilization effect is defined in SOCCR1 as the "phenomenon in which plant growth increases (and agricultural crop yields increase) due to the increased rates of photosynthesis of plant species in response to elevated concentrations of CO_2 in the atmosphere." SOCCR1 concluded that the CO_2 fertilization effect was widespread, but whether enhanced photosynthesis would translate into a persistent land carbon sink was unclear (CCSP 2007). The global land carbon sink, calculated as the difference between human emissions and carbon accumulating in the atmosphere and ocean, has grown from 0.2 ± 0.5 petagrams of carbon (Pg C) per year in the 1960s to 3.0 ± 0.7 Pg C per year in 2014 (Le Quéré et al., 2015). This change consists of the effects of land-use change and the residual land sink (Le Quéré et al., 2016). The residual carbon sink is carbon that is stored on land but is calculated as the remainder of other observed carbon sinks rather than observed itself. Growth in the residual sink is attributed to global changes in CO_2, nitrogen deposition, and climate in both observational studies and modeling efforts (Ballantyne et al., 2012; Le Quéré et al., 2016; Schimel et al., 2015). However, predicting how the land carbon sink will respond to changing atmospheric CO_2 is challenging because the land sink is inferred by accounting rather than experimental testing. The research community has evaluated the CO_2 fertilization effect through experimental

Box 17.1 Short-Term Physiological Effects of CO_2 on Plants

Studies lasting from weeks up to more than a decade show that the response of vegetation to rising carbon dioxide (CO_2) is influenced by climate and environmental changes, which create complex feedbacks to the carbon cycle. Carbon gains from CO_2 fertilization lead to faster cycling or more carbon storage. The balance of the effects of climate and CO_2 fertilization on terrestrial carbon storage is uncertain.

Physiological Adjustment to Rising CO_2

Increased Photosynthesis per Leaf Area

- More efficient plants lead to increased biomass or increased rate of biomass cycling.
- Faster plant growth leads to limitation by nutrients or greater investment in roots (or both).
- Larger or faster-growing plants lead to greater carbon inputs into soil.

Decreased Water Conductance per Leaf Area

- Increased photosynthesis and decreased water use increase plant water-use efficiency.
- Reduced investment in photosynthetic enzymes increases plant nitrogen-use efficiency.
- Reduced investment in photosynthetic enzymes may result in total or partial loss of the fertilization effect.

Plant Species Responses

- Plants with CO_2-concentrating mechanisms (i.e., C_4 or crassulacean acid metabolism [CAM] plants) experience higher water-use efficiency but no direct effect on photosynthesis.
- Changing competition may result in new plant communities.
- Young, actively growing forests may represent an upper bound to increased productivity; there is little demonstrated enhancement of mature, slow-growing forests.
- Fast-growing species (e.g., weeds) may see more enhancement than slow-growing species.

Food and Crop Responses

- Decreased plant enzymes mean that herbivores need to harvest more leaf area to eat the same amount of protein.
- For the same input, crop yields likely will increase, while the protein content of crops probably will decrease.
- Pollen production may increase.

manipulations such as Free-Air CO_2 Enrichment (FACE) projects (see Figure 17.1, p. 693), tree rings, observational networks, and modeling experiments.

Plants take up carbon through the process of photosynthesis and synthesize biomass (e.g., leaves, wood, and roots) from simple, carbon-rich sugars derived from CO_2. As CO_2 increases in the atmosphere, plants can photosynthesize more quickly. Plants take up CO_2 through the same pores (stomata) from which they lose water, leading to a balance between CO_2 uptake and water loss. Rising CO_2 increases carbon uptake per unit of water lost, allowing plants to close their stomata and therefore become more efficient in water usage (see Box 17.1, Short-Term Physiological Effects of CO_2 on Plants, this page). These physiological effects play out differently in different types of plants and under different environmental conditions. Twenty years of CO_2-enrichment experiments have shown that elevated CO_2 enhances photosynthetic carbon gain over the long term for certain ecosystem types but only over the short term for others (Leakey et al., 2009; Leuzinger et al., 2011; Norby and Zak 2011). Plant communities dominated by trees and grasses generally show greater stimulation of photosynthetic carbon uptake compared to

that of legumes, shrubs, and nonleguminous crops (Ainsworth and Rogers 2007).

Net primary production (NPP) is calculated as either the balance between carbon gained through photosynthesis and lost through respiration or the sum of all growth over a year. With increased CO_2, NPP is enhanced by ~23% across a broad range of early successional forests (Norby et al., 2005). These results probably are not indicative of all forests, and smaller responses have been observed in the limited number of studies carried out in old-growth temperate, boreal, and tropical forests (Hickler et al., 2008; Körner et al., 2005). Also clear is that the temporal pattern of NPP responses to elevated CO_2 differs among forests (e.g., McCarthy et al., 2010; Norby et al., 2010).

Plants balance carbon gain and water loss. Stomatal conductance is depressed at elevated CO_2, so plants may reduce water loss without reducing carbon gain, an observation which has been noted at the leaf and canopy scales (Keenan et al., 2013; Leakey et al., 2009; Peñuelas et al., 2011). Observations of decreased canopy evapotranspiration at elevated CO_2 are therefore coupled with those of increased soil moisture. Crop carbon accumulation and water-use efficiency can be enhanced under drought conditions (Blum 2009; Morison et al., 2008), but extreme droughts may reduce or eliminate these enhancements (Gray et al., 2016).

Plant growth over years is not limited by CO_2 alone (Körner 2015). If another environmental factor limits growth, then experimentally increasing CO_2 causes diminished enhancement of photosynthesis and plant production (Ainsworth and Long 2005; Ainsworth and Rogers 2007). For example, nitrogen is sequestered in long-lived biomass and soil pools and may not always be readily available to plants. In this case, nitrogen limitation inhibits increases in plant production associated with elevated CO_2, a process which is referred to as a negative feedback. In systems where nitrogen cycling did not reduce sink strength, the effects of CO_2 fertilization on increasing NPP persisted (Drake et al., 2011; Finzi et al., 2006). The effects of rising CO_2 on tree biomass may be inferred from tree-ring records, but results are mixed; some studies show no effect from changing CO_2, and others show increased growth or water-use efficiency (Andreu-Hayles et al., 2011; Cole et al., 2009; Knapp and Soulé 2011; Koutavas 2013).

Because of these complications, whether rising CO_2 will lead to larger standing biomass and carbon storage is unclear, in part because of the enormous complexity of the entire system (Norby and Zak 2011; Leuzinger and Hattenschwiler 2013). While instantaneous and annual fluxes of carbon are well studied in the FACE literature, the allocation of carbon to stems, roots, and leaves, for example, varies among experiments (DeLucia et al., 2005), and enhancement of multidecadal carbon stocks (e.g., woody biomass and soil organic matter) is not well studied (Leuzinger and Hattenschwiler 2013; Norby and Zak 2011). Increased carbon supply from plants can lead to heightened activity of soil fauna and more rapid cycling of carbon rather than increased carbon storage in soils (Phillips et al., 2012; van Groenigen et al., 2011, 2014). Because observed changes in soil carbon were small over the timescale of the FACE studies (3 to 16 years), firm conclusions about the impact of elevated CO_2 on soil carbon remain elusive (Luo et al., 2011). In general, research suggests that large effects of rising CO_2 on carbon storage in soils are limited (Schlesinger and Lichter 2001), although the combined effects of CO_2 and nitrogen deposition and rising temperatures may significantly affect soil carbon loss (Zhou et al., 2016).

17.5 Carbon Cycle Feedbacks of Rising CO_2

Climate and rising atmospheric CO_2 can alter the amount of carbon taken up or released by ecosystems and the ocean. Rising temperatures influence the response of the carbon cycle to rising CO_2 in diverse and complicated ways, yielding both positive and negative feedbacks (Deryng et al., 2016; Dieleman et al., 2012; Holding et al., 2015). Positive feedbacks tend to be additive of the original effect,

negative feedbacks tend to counteract the original effect. Overall, rising temperatures tend to release more land and ocean carbon into the atmosphere, while rising CO_2 is projected to increase land and ocean uptake (Friedlingstein et al., 2006). However, the importance of this positive feedback is variable according to different locations and time frames. Earth System Model assessments that incorporate carbon cycle feedbacks to projected climate change show that the combined effects of climate change result in an overall larger increase in CO_2 concentrations, thus contributing to additional climate warming (a positive feedback). However, this feedback is highly uncertain due to its dependence on various factors, so different studies may report large ranges in predicted CO_2 concentrations (Blok et al., 2010; Elberling et al., 2013; Hodgkins et al., 2014; McCalley et al., 2014; Schneider von Deimling et al., 2012; Schuur et al., 2009). Temperature also indirectly influences radiative CO_2 effects. For example, increased evaporation from the ocean in a warmer world yields higher atmospheric water vapor concentrations that further amplify the impact of CO_2 on climate warming (Myhre et al., 2013). Another chapter in this report presents a broader discussion of the impacts of multiple environmental changes (see Ch. 19: Future of the North American Carbon Cycle, p. 760).

On land, the direct effect of rising CO_2 on plant photosynthesis and growth interacts with rising temperature (Gray et al., 2016; Zhu et al., 2016). Rising CO_2 increases the photosynthetic temperature optimum (Long 1991) because of the decreasing relative solubility of CO_2 versus oxygen at higher temperatures (Jordan and Ogren 1984). While photosynthesis, respiration, and decomposition sensitivities to temperature act on short timescales of decades, chemical weathering sensitivities act over several hundred thousand years and are largely responsible for moderating CO_2 levels throughout the geological record. Rising temperatures affect biogeochemical processes through enhanced NPP, faster microbial decomposition of organic matter and increased emissions of CO_2 from microbial respiration in soils, and increased rates of chemical weathering (Galloway et al., 2014). However, interactions between rising CO_2 and temperature are complicated by nonuniform warming patterns, and research shows that climate warming can either stimulate or suppress plant productivity depending on the season and region (Xia et al., 2014). In the cryosphere, higher temperatures thaw permafrost and melt ice, processes which release stored CO_2 and CH_4 back into the atmosphere (Schneider von Deimling et al., 2012).

Chemical weathering of minerals, which consumes CO_2 from the atmosphere, provides an important feedback mechanism for CO_2 in the carbon cycle (Berner 1992; Colbourn et al., 2015; Kump et al., 2000; see Ch. 12: Soils, p. 469). Carbon dioxide is found in soils and surficial deposits because of plant and microbial respiration as well as chemical weathering of minerals. Carbonic acid, which is formed naturally when CO_2 becomes dissolved into infiltrating rainwater, can dissolve primary minerals, a process that consumes CO_2. Also, $CaCO_3$ may precipitate in soils and surficial deposits if concentrations are high enough, a process that may be enhanced by low soil moisture and in semiarid and arid climates (Berner 1992). The rates of mineral reactions depend on several factors, including temperature, pressure, and mineral saturation state, all of which are influenced by climate. As temperatures rise, weathering rates of most minerals increase, leading to greater CO_2 consumption (Brady and Carroll 1994; Velbel 1993). Precipitation (e.g., rain and snowmelt) flushes solutes away, lowering the saturation state for primary minerals in solution, thereby promoting higher mineral weathering rates (Clow and Mast 2010; Kump et al., 2000). Thus, greater precipitation would lead to lower mineral saturation states, higher weathering rates, and greater CO_2 consumption (Clow and Mast 2010). These feedback mechanisms have the potential to help mitigate the effects of rising atmospheric CO_2 concentrations, but their effects will vary spatially and temporally in concert with changes in temperature and precipitation. For example, while the northeastern United States may see relatively strong increases in weathering rates because of increasing

temperature and precipitation (IPCC 2013), the Southwest might experience more mixed impacts because of increasing temperature but decreasing precipitation (IPCC 2013).

17.6 Consequences for Ecosystem Services

Oceanic ecosystem services critical for human survival, such as the provision of fish and seafood, carbon storage, coastal protection by reefs, and climate modulation, face significant risks from the combined effects of ocean acidification, warming, and sea level rise (Gattuso et al., 2015). Under the current rate of CO_2 emissions, most marine organisms evaluated to date will face a very high risk of impacts by 2100, and some, including coral reefs (Hughes et al., 2017; Ainsworth et al., 2016; Hughes et al., 2018) and bivalve shellfish (Kroeker et al., 2013), already face moderate to high risk today (Gattuso et al., 2015; see Figure 17.5, p. 704). For future scenarios without significant mitigation of CO_2 emissions, predicted impacts to ocean ecosystem services are moderate for the early decades of this century but put all ecosystem services at high or very high risk by 2100 (Gattuso et al., 2015).

17.6.1 Biodiversity

Rising CO_2 will affect species differentially. Described here are the direct effects of rising CO_2 rather than the impacts of warming, which are discussed comprehensively in CSSR (USGCRP 2017). Acidification by CO_2 has been associated with a decline in shell-bearing benthic organisms (Hall-Spencer et al., 2008; Kroeker et al., 2011). Declines in oyster spat survival at a commercial hatchery in the U.S. Pacific Northwest that temporarily jeopardized the region's oyster aquaculture industry have been definitively attributed to ocean acidification (Barton et al., 2015). Laboratory studies and meta-analyses have provided evidence for and against detrimental effects on marine biodiversity (Bijma et al., 2013; Dupont et al., 2010; Hendriks and Duarte 2010; Hendriks et al., 2010). Foundational organisms such as microbial populations, while not deeply studied, also demonstrate a range of positive to negative responses to ocean acidification (Bunse et al., 2016). The effects of ocean acidification on marine ecosystem structure are only now being identified. Models simulating ocean acidification's impacts on bivalve shellfish have shown a restructuring of the entire California Current ecosystem by a combination of indirect predator-prey effects (Busch et al., 2013; Kaplan et al., 2010). Another model showed substantial restructuring of phytoplankton communities under ocean acidification and warming (Dutkiewicz et al., 2015), but studies still have not determined whether this restructuring would have significant effects on phytoplankton community function or food-web relationships.

On land, elevated atmospheric CO_2 studies have demonstrated that seed yield can be increased (LaDeau and Clark 2001, 2006). In some crop species, increased seed production was accompanied by reduced quality (Ainsworth et al., 2002) but not in tree species (Way et al., 2010). Species show different growth responses to rising CO_2 (Dawes et al., 2011), possibly giving dominant plants an advantage (McDonald et al., 2002; Moore et al., 2006) and leading to changes in forest structure. However, the impact on biodiversity will depend on ecological responses that will remain uncertain without long-term study of ecological responses to rising CO_2 (Alin et al., 2015; Carey and Cottingham 2016; Elmendorf et al., 2016; Schimel et al., 2011).

17.6.2 Food and Fiber Provision

Ocean acidification is likely to have long-term effects on the population and diversity of fish and invertebrates, including economically and ecologically important shellfish (Pörtner et al., 2004). Although difficult to untangle, the combined effects of resource competition, pollution, overfishing, habitat modification, acidification, water temperature increases, and climate-driven changes on small-scale fisheries and aquaculture are likely to result in widespread changes in ocean ecosystems and in the fisheries themselves (HLPE 2014).

The impacts of ocean acidification on the food value, quality, and market value of marine species

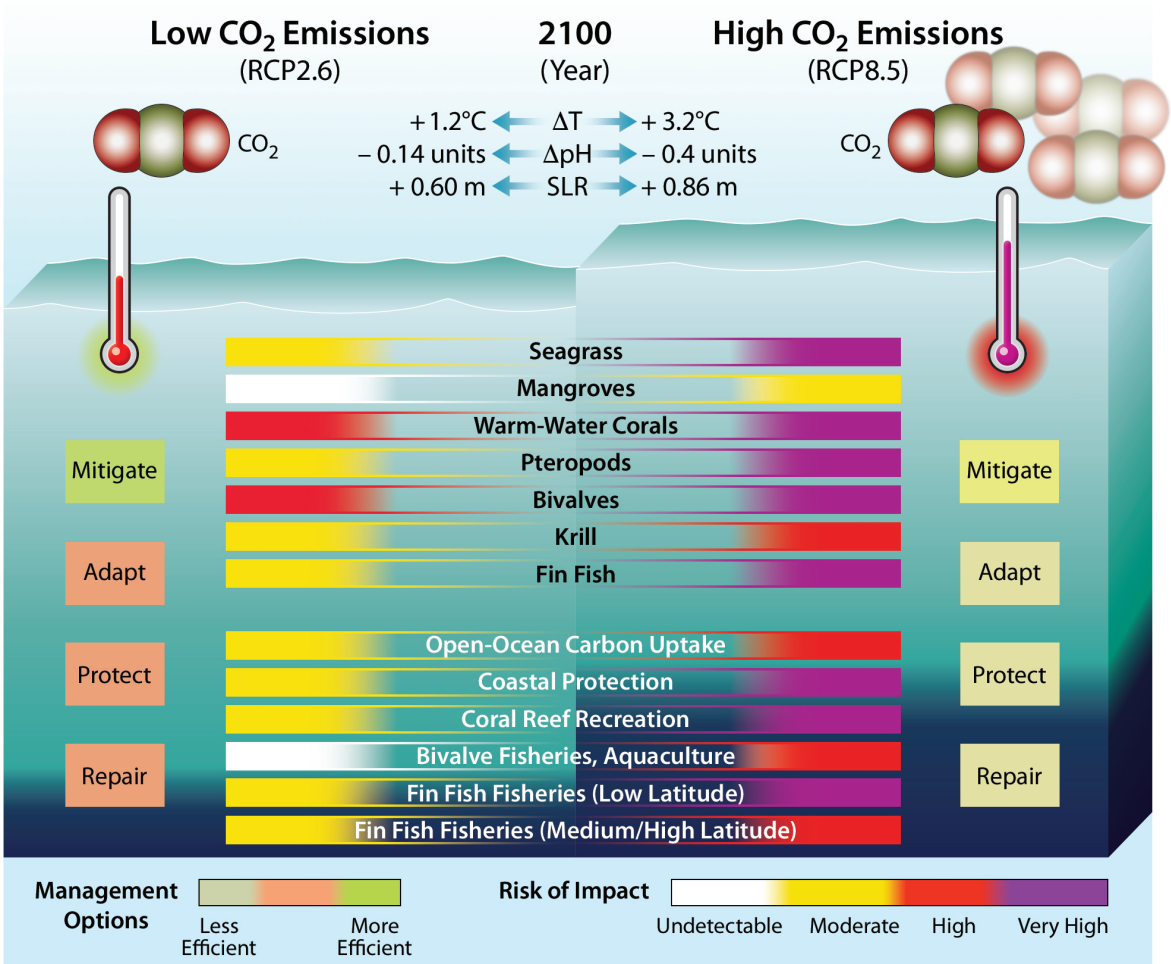

Figure 17.5. Ocean Impacts Projected by High and Low Carbon Dioxide (CO_2) Emissions Scenarios. Impacts on organisms and ecosystem services are shown—along with effects of acidification, warming, and sea level rise on ocean physics and chemistry—for both a low CO_2 emissions scenario (Representative Concentration Pathway [RCP]2.6), and for a high CO_2 scenario (RCP8.5). (See Ch. 19: Future of the North American Carbon Cycle for RCP explanations, p. 760.) Physical impacts on the ocean due to higher atmospheric CO_2 levels are largely related to the climatic effects of CO_2 and other radiatively active, anthropogenically released gases. These impacts include higher sea levels and shallower oceanic mixing (right-side water column, shown by a taller water level and shallower light aqua mixed layer). More severe risks of impacts from higher oceanic CO_2 levels on ocean taxa (top group, black text) in higher CO_2 emissions scenarios (center right) correspond to higher risks of impacts on ecosystem services (bottom group, white text, center right). Management options (i.e., activities that will mitigate, adapt, protect, or repair marine systems) are more numerous and more effective in lower CO_2 scenarios (far left) compared with those in a higher CO_2 world (far right). [Figure source: Adapted from Gattuso et al., 2015.]

have yet to be conclusively determined. One preliminary study (Dupont et al., 2014) notes that the taste and texture of pink shrimp (*Pandalus borealis*) were poorer when the shrimp had been raised under more acidified conditions. Assuming that ocean acidification slows the growth of bivalve shellfish in the wild as it does in laboratory studies (Kroeker et al., 2013), harvest of the largest size class of sea scallop meat, which fetches a market price premium, is projected to decline under acidification (Cooley

et al., 2015). The growth-retarding effects of acidification on king and Tanner crab as reported by Long et al. (2013a, 2013b) are projected to harm fishery revenues (Punt et al., 2016), but the implications of acidification for the market quality of Alaskan crabs (e.g., taste and texture) are not yet known. If the laboratory and model results reviewed above hold true in natural ecosystems, ocean acidification is likely to decrease the volume or quality of marine harvests beyond simply the impacts on oyster aquaculture observed to date. The larval production shortage in the mid-2000s experienced by the Pacific Northwest oyster aquaculture industry that was conclusively attributed to ocean acidification remains the bellwether example of impacts to fisheries from rising CO_2 (Barton et al., 2015).

Terrestrial provisioning services (e.g., crops and livestock) also are responding to rising CO_2. For example, crop production increased in response to experimentally elevated CO_2 (Leakey et al., 2009), but increases in crop yield were accompanied by decreases in seed quality (Myers et al., 2014). Physiological changes also led to increased herbivory in some crops (DeLucia et al., 2012; Dermody et al., 2008). The effects of rising CO_2 on crop yield are tempered by other global changes. Corresponding increases in ground ozone decreases productivity (Morgan et al., 2006), and increased drought may remove the positive effects of rising CO_2 entirely (Gray et al., 2016). Carbon dioxide fertilization can have either direct or indirect consequences on agriculture. At higher levels of atmospheric warming and at low latitudes, model simulations show significant reductions in yields for all major crops, even with the positive benefits of CO_2 fertilization (Challinor et al., 2014). Indirect effects of rising CO_2 include the reduction in nutrient content and digestibility of pasture for livestock (Tubiello et al., 2007) and reductions in protein content by 10% to 14% in the edible portions of wheat, rice, barley, and potato and by 1.5% in soybeans (Müller et al., 2014; Taub et al., 2008).

Terrestrial food and fiber production over the next century may be more profoundly influenced by climate change than by rising CO_2 itself. Climate changes could include heatwaves during growing seasons, droughts and lengthening of dry spells, and rising sea levels (Melillo et al., 2014; Nelson et al., 2014; Wiebe et al., 2015). The greater the greenhouse gas concentrations, the greater the change in the climate and climate-associated risks for agriculture and food security (Brown et al., 2015).

17.6.3 Carbon Storage in Vegetation and Soils

Vegetated coastal ecosystems store CO_2 in seagrasses, marshes, kelp, and mangroves at rates comparable with those of forest ecosystems (McLeod et al., 2011). This "blue carbon" is believed to be an important sink for atmospheric CO_2, but coastal habitats are under strong human-driven pressures worldwide including habitat destruction, rising ocean temperatures, sea level rise, and sediment starvation (see Ch. 15: Tidal Wetlands and Estuaries, p. 596). For example, erosion of coastal wetlands or thawing of coastal Arctic permafrost exposes buried organic carbon, which can either be respired *in situ* to release CH_4 or CO_2, exacerbating atmospheric warming, or be released to nearshore waters and respired there, contributing to local acidification (Aufdenkampe et al., 2011; see Ch. 11: Arctic and Boreal Carbon, p. 428). Seagrasses may help mitigate ocean acidification locally (Hendriks et al., 2014), underscoring the double benefit of protecting blue carbon habitats.

Carbon on land is stored in vegetation and soils. Forests account for approximately 66% of the land carbon sink (see Ch. 2: North American Carbon Budget, p. 71, and Ch. 9: Forests, p. 365), a percentage which could increase if strategies were applied to minimize forest losses from deforestation. However, carbon sinks change with the age of forest regrowth—the rate of carbon accumulation is rapid in young forests but typically quite low in old-growth forests. Restoring the organic content of agricultural and natural soils also can increase soil carbon storage (Lal 2003). Historically, soils have lost vast amounts of carbon when transitioning from natural to human-modified landscapes (e.g.,

through urbanization and forest and agricultural management; see also Ch. 5: Agriculture, p. 229, and Ch. 12: Soils, p. 469), but gauging the effect of land management on carbon storage is challenging. The land carbon sink is calculated using bookkeeping methods that sum together carbon into different respective ecosystem compartments (e.g., land, ocean, and atmosphere) at a variety of scales. The carbon sink is typically inferred by the existence of a residual (i.e., unaccounted) sink in the global carbon budget. Therefore, the effects of land management can be difficult to detect and attribute using carbon balance accounting methods (Erb et al., 2013).

17.6.4 Coastal Protection by Corals

In low-latitude areas around the world, coral reefs are particularly important for protecting coastlines, but the combined effects of rising temperature and ocean acidification slow the growth of stony coral reefs (Muehllehner et al., 2016; Wong et al., 2014), hindering their ability to grow or recover from damage (Hughes et al., 2017; Ainsworth et al., 2016; Hughes et al., 2018). Carbonate sediments also are being dissolved by ocean acidification, while sea level also rises; the net effect has accelerated the relative rate of sea level rise near Florida, Hawai'i, and the U.S. Virgin Islands, exposing those coastal communities to heightened risk of flooding (Yates et al., 2017). Globally, the loss of the three-dimensional structure of the reef could expose 200 million people to greater effects of storms and tsunamis (Ferrario et al., 2014). People living in the low-elevation coastal zone (LECZ), below 10 m in elevation (Vafeidis et al., 2011), face a higher risk of coastal hazards such as flooding and sea level rise due to climate change (Lichter and Felsenstein 2012). In the United States, population in the LECZ is forecast to increase by 188% from 23 million in 2000 to 44 million in 2060 (Neumann et al., 2015), so losses of coral reefs that protect coastlines heighten overall coastal community risk.

17.6.5 Water Availability

Reduced transpiration due to increased plant water-use efficiency (Leakey et al., 2009; Norby and Zak 2011) may allow more water to pass through soils and enter freshwater ecosystems. As discussed in Ch. 13: Terrestrial Wetlands, p. 507, and Ch. 14: Inland Waters, p. 568, inland waters act as hotspots for the degradation and outgassing of carbon originating from both terrestrial and aquatic sources. Increases in precipitation events, along with reductions in transpiration (Charney et al., 2016; van der Sleen et al., 2014), may facilitate the movement of materials from the landscape into water systems, altering ecosystem structure and function as seen extensively on Lake Erie (Smith et al., 2015). Conversely, the drying of systems that receive less precipitation will dramatically influence the timing of rainfed and snowmelt-driven ecosystems and municipalities reliant on surface waters for agriculture, fisheries, industry, and drinking water (Clow et al., 2010; Rao et al., 2004).

17.7 Synthesis, Knowledge Gaps, and Outlook

17.7.1 Current State of Knowledge

The rise of atmospheric CO_2—attributable primarily to human-caused fossil fuel emissions and land-use change—has been dampened by carbon uptake by the ocean and terrestrial biosphere. Nevertheless, today's atmospheric CO_2 levels are higher than at any time in at least the past 800,000 years (Hönisch et al., 2012). Uptake of this fossil fuel CO_2 has caused documented direct and indirect effects on terrestrial and oceanic systems and processes in different regions of North America and the rest of the planet. The capacity of these systems to continue to act as carbon sinks is not certain because the systems are dynamic and influenced by feedbacks related to CO_2 levels (see Section 17.3, p. 695). Another major set of consequences stems from the atmospheric warming caused by rising CO_2; weather and climate changes affect nearly every terrestrial and oceanic process (see Section 17.3–17.5) and often lead to additional feedbacks. Although reviewed in detail in other reports, including the IPCC AR5 (IPCC 2013) and CSSR (USGCRP 2017), these consequences deserve mention here because of their combined effects

with CO_2 on systems and processes throughout the land and ocean domains.

17.7.2 Key Knowledge Gaps and Opportunities

Research has uncovered many of the direct and indirect responses of natural systems to rising CO_2, but mechanisms often remain unclear. Since the SOCCR1 report, increasing computational power has enabled the development of complex models to examine the consequences of rising CO_2 and a changing carbon cycle. Observational and modeling studies, such as the new generation of FACE experiments now underway, are being planned in concert to enable strategic data collection. Some of these approaches allow for limitations of multiple resources (e.g., nitrogen and phosphorus), which could lead to more realistic projections of the terrestrial carbon sink's response to rising CO_2. As Figure 17.1, p. 693, illustrates, there are current FACE experiments in the Northwest, Northeast, Southern Plains, or any tropical ecosystem within the U.S. territories. While most experiments are in mesic (wet) or temperate ecosystems (see Figure 17.6, p. 708), understanding the response of tropical forests or coniferous boreal forests is critical to account for carbon cycle feedbacks. Oceanic models are providing insight into ecosystem relationships and dynamics under global change and into the biophysical underpinnings of ocean-atmosphere interactions. Despite these insights, knowledge of how multiple global change factors affect modeled processes would greatly improve model forecast ability. In contrast, most experimental manipulations are single-factor experiments in which only one variable is manipulated.

Disentangling the impacts of rising CO_2 and other concurrent changes in climate, land use, nutrient cycles, and atmospheric chemistry across all ecosystems likely requires long-term, sustained carbon cycle observations and monitoring of ecosystem and socioeconomic consequences. Long-term observing networks are critical to managing ecosystems sustainably and adaptively (e.g., Schindler and Hilborn 2015), and a focus on data management and interoperability across data platforms would improve understanding of long-term responses to rising CO_2 (Ciais et al., 2014). Few experiments on land or in the ocean extend to a decade in length, and therefore the long-term ecosystem responses are not clear.

Pörtner et al. (2014) conclude that there is medium to high agreement that ecosystem services will change. However, the effects of rising CO_2 on biodiversity and vegetation changes after disturbance remain poorly understood and could result in altered ecosystem function and different ecosystem services. This lack of understanding also limits the ability to anticipate recovery from acute disturbances such as storms, fires, disease, or insect outbreaks.

As forecasts of future conditions improve, investigating past conditions on Earth is still important. Over short timescales, historical terrestrial work is limited to studies that involve reconstructions of plant growth (e.g., tree rings). Exploring historical conditions decades or centuries before via ice core analysis, seafloor sediment core studies, and geological research will continue to uncover aspects of prior ages that are analogous to today, aiding the anticipation of potential changes in the Earth system as global change continues.

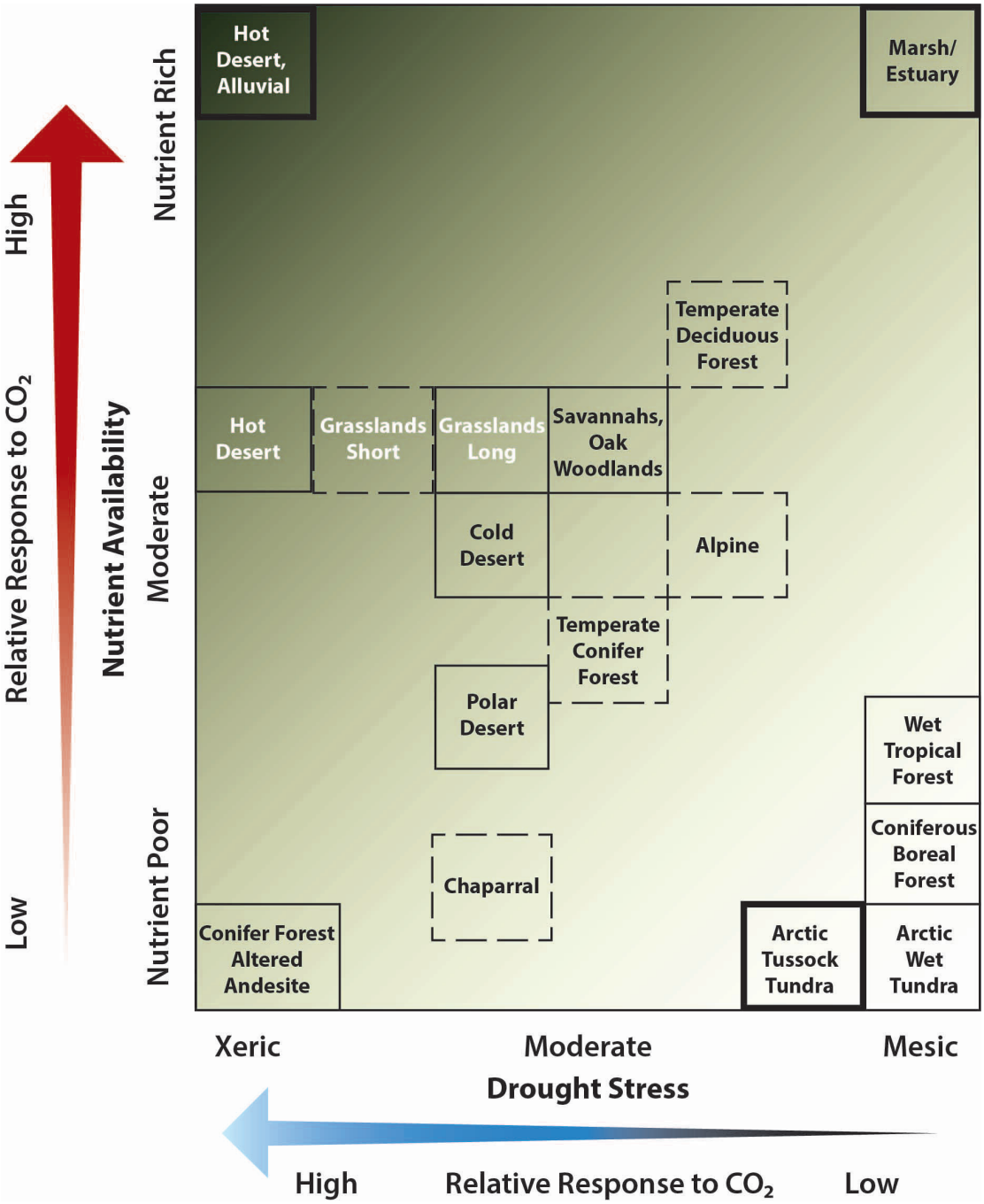

Figure 17.6. Hypothesized Ecosystem Responses to Elevated Carbon Dioxide (CO_2) Relative to Nutrient and Water Availability. Field studies, including Free-Air CO_2 Enrichment (FACE) experiments, have been conducted in desert, grasslands, chaparral, alpine, and temperate deciduous forests but not in tropical forests or coniferous boreal forests. Increasingly darker green indicates greater relative response to CO_2, based on the assumptions that response increases with drought stress and with nutrient availability. [Figure source: Reprinted from Norby et al., 2016 (originally adapted from Mooney et al., 1991).]

SUPPORTING EVIDENCE

KEY FINDING 1

Rising carbon dioxide (CO_2) has decreased seawater pH at long-term observing stations around the world, including in the open ocean north of Oahu, Hawai'i; near Alaska's Aleutian Islands; on the Gulf of Maine shore; and on Gray's Reef in the southeastern United States. This ocean acidification process has already affected some marine species and altered fundamental ecosystem processes, and further effects are likely (*high confidence, likely*).

Description of evidence base

The atmospheric record indicates that both the ocean and land carbon sinks have increased as CO_2 has risen (Le Quéré et al., 2016). Modern-day ocean observations have confirmed that seawater pH is decreasing because of atmospheric CO_2 uptake (Feely et al., 2004, 2009; Gattuso et al., 2015; Orr et al., 2005). Time-series stations around North America (near Hawai'i, Alaska, Washington, California, Georgia, and Maine) have documented decreased pH below preindustrial levels for some or all of the annual cycle (Sutton et al., 2016). Effects on marine life and fundamental ecosystem processes or characteristics, including calcification, biodiversity, growth rates, and nitrogen fixation, are reviewed in this chapter; they are documented in detail in Bijma et al. (2013), Bunse et al. (2016), Dupont et al. (2010), Fu et al. (2007, 2012), Hendriks and Duarte (2010), Hendriks et al. (2010), Hofmann et al. (2010), Hutchins et al. (2013), Kroeker et al. (2013), Meyer and Riebesell (2015), Riebesell and Tortell (2011), and Riebesell et al. (2007), among others. Future effects are projected by observational (Pespeni et al., 2013; Wootton et al., 2008), integrative (Boyd et al., 2014), and modeling (Dutkiewicz et al., 2015) studies.

Major uncertainties

In most cases, observed biological effects have not been mechanistically attributed to pH or carbonate and bicarbonate ion concentration changes. Laboratory studies may not perfectly reproduce the responses of organisms in nature, where environments and drivers are more complex and numerous. Genetic, behavioral, and phenotypic plasticity (flexibility) have not been evaluated for most of the species investigated in laboratory studies.

Estimated likelihood of impact or consequence, including short description of basis of estimate

Variation within populations (plasticity) and the existence of many competing environmental drivers could offset the effects of ocean acidification on some marine populations, but to an uncertain extent. Research has demonstrated effects on large groups of marine organisms (e.g., bivalve shellfish and stony corals) unambiguously enough to ascertain that continuing negative impacts to these communities are likely.

Summary sentence or paragraph that integrates the above information

Rising CO_2 has decreased seawater pH (*very high confidence*). This process of ocean acidification has affected some marine species (*very high confidence*) and altered fundamental ecosystem processes (*high confidence*), with further effects likely (*high confidence*). Continuing impacts are probable, but plasticity and the existence of other environmental drivers could offset the effects of ocean acidification on some marine populations to an uncertain extent.

KEY FINDING 2

While atmospheric CO_2 rises at approximately the same rate all over the globe, its non-climate effects on land vary depending on climate and dominant species. In terrestrial ecosystems, rising atmospheric CO_2 concentrations are expected to increase plant photosynthesis, growth, and water-use efficiency, though these effects are reduced when nutrients, drought, or other factors limit plant growth (*very high confidence, very likely*). Rising CO_2 would likely change carbon storage and influence terrestrial hydrology and biogeochemical cycling, but concomitant effects on vegetation composition and nutrient feedbacks are challenging to predict, making decadal forecasts uncertain.

Description of evidence base

Research definitively shows that the bodies of marine and terrestrial organisms have incorporated CO_2 released from the burning of fossil fuels, based on the change in isotope ratios within their biological material (Fraile et al., 2016; Hilton et al., 2006; Suess 1955).

On land, the historical record of the impact of rising CO_2 is more complex. Physiological theory suggests that, as CO_2 rises, photosynthesis should increase. Using preserved plant specimens, isotopomer analysis appears to support this physiological prediction (Ehlers et al., 2015), though this is a novel technique. The effects of rising CO_2 on tree biomass over multiple decades may be inferred from tree-ring records, but they provide mixed results (Andreu-Hayles et al., 2011; Cole et al., 2009; Knapp and Soulé 2011; Koutavas 2013). Studies from a wide range of forest types across broad geographic regions have observed changes in the ratio of the ^{13}C isotope to the ^{12}C isotope ($\delta^{13}C$), observations which imply trees have experienced increased water-use efficiency as CO_2 has risen over the last two centuries, but growth was not clearly stimulated by rising CO_2 (Peñuelas et al., 2011).

Rising CO_2 tends to make plants close their stomata and thus use water more efficiently. The primary enzyme responsible for CO_2 uptake, ribulose-1,5-bisphosphate carboxylase-oxygenase (RUBISCO), accounts for a substantial portion of every plant's nitrogen requirement. As CO_2 rises, less RUBISCO is required for the same carbon gain, so plants become more efficient in nutrient use. These physiological effects play out differently in various types of plants and under diverse environmental conditions. Plants that lack a CO_2 concentration mechanism and pass a 3-carbon sugar molecule into the Benson-Calvin cycle (C_3 plants) are more likely to show an instantaneous photosynthetic response than plants with a CO_2 concentration mechanism like C_4 plants (that pass a 4-carbon sugar molecule to the Benson-Calvin cycle) or those that use crassulacean acid metabolism (CAM).

Twenty years of CO_2 enrichment experiments have shown that elevated CO_2 enhances photosynthetic carbon gain over the long term for certain ecosystem types but only over the short term for others (Leakey et al., 2009; Leuzinger et al., 2011; Norby and Zak 2011). Plant communities dominated by trees and grasses generally have shown greater stimulation of photosynthetic carbon uptake compared to that of legumes, shrubs, and nonleguminous C_3 crops (Ainsworth and Rogers 2007).

Net primary production (NPP) is calculated as either the balance between carbon gained through photosynthesis and lost through respiration or the sum of all growth over a year. NPP is

enhanced by ~23% across a broad range of early successional forests in response to elevated CO_2 (Norby et al., 2005). These results are likely not indicative of all forests, and smaller responses have been observed in the limited number of studies carried out in old-growth temperate, boreal, and tropical forests (Hickler et al., 2008; Körner et al., 2005). Also clear is that the temporal pattern of NPP responses to elevated CO_2 differs among forests. For example, McCarthy et al. (2010) reported that NPP in coniferous forests was enhanced by 22% to 30% and sustained over 10 years of exposure to 550 parts per million (ppm) of CO_2. In contrast, Norby et al. (2010) found that NPP was significantly enhanced for 6 years in hardwood forest plots exposed to 550 ppm CO_2 (compared with plots under current ambient CO_2), after which time the enhancement of NPP under elevated CO_2 declined from 24% to 9%.

Plants balance carbon gain and water loss. Stomatal conductance is depressed at elevated CO_2, so plants may reduce water loss without reducing carbon gain. This physiological effect has been observed at the leaf and canopy scales (Keenan et al., 2013; Leakey et al., 2009; Peñuelas et al., 2011) and represents the major mechanism leading to observations of decreased canopy evapotranspiration under elevated CO_2. For the hydrological cycle, this mechanism results in increased soil moisture. Even plants with CO_2 concentration mechanisms (i.e., C_4 and CAM plants) may experience increased water-use efficiency without any direct stimulation in photosynthesis (Leakey et al., 2009). Under drought conditions, elevated CO_2 may not directly stimulate photosynthesis in C_4 plants but can indirectly increase carbon gain by increasing water-use efficiency.

Physiological theory and experimental evidence indicate that rising CO_2 increases the photosynthetic temperature optimum (Long 1991) because of the decreasing relative solubility of CO_2 versus oxygen at higher temperatures (Jordan and Ogren 1984). These results imply that biomes that experience high temperatures may experience disproportionately enhanced photosynthesis and growth. Interannual variation in the increased growth of Lobolly pine trees was disproportionately enhanced by experimentally elevated CO_2 in warmer years (Moore et al., 2006).

Plant growth is not limited by CO_2 alone (Körner 2015). If, for example, another environmental factor limits growth, then experimentally increasing CO_2 has reduced effects on photosynthesis and growth (Ainsworth and Rogers 2007). This outcome is called "sink limitation." Research suggests that nitrogen limitation may be one mechanism leading to declining NPP responses to elevated CO_2 in some ecosystems (Norby et al., 2010).

Nitrogen is sequestered in long-lived biomass and soil pools and may not be readily available to plants under some conditions. In this case, nitrogen limitation inhibits increases in plant production associated with elevated CO_2, an effect which is referred to as a negative feedback. In systems where nitrogen supply was sufficient, CO_2 fertilization effects on NPP persisted (Drake et al., 2011; Finzi et al., 2006). Nevertheless, elevated CO_2 also increases photosynthetic nitrogen-use efficiency, defined as the net amount of CO_2 assimilated per unit of leaf nitrogen (Ainsworth and Rogers 2007; Bader et al., 2010; Leakey et al., 2009).

Elevated atmospheric CO_2 experiments have demonstrated that seed yield can be increased (LaDeau and Clark 2001, 2006). In some crop species, increased seed production was accompanied by reduced quality (Ainsworth et al., 2002), but this was not observed in tree species (Way et al., 2010). Species show different growth responses to rising CO_2 (Dawes et al., 2011), and

dominant plants may have an advantage with rising CO_2 (McDonald et al., 2002; Moore et al., 2006), leading to changes in forest structure.

Major uncertainties

Unclear is whether rising CO_2 will lead to larger standing biomass and carbon storage or simply faster cycling of carbon (Norby and Zak 2011). While instantaneous and annual fluxes of carbon are well studied in the Free-Air CO_2 Enrichment (FACE) literature, the allocation of carbon to different pools varies between experiments (DeLucia et al., 2005), and enhancement of multidecadal carbon stocks (e.g., woody biomass and soil organic matter) is not well studied (Leuzinger and Hattenschwiler 2013; Norby and Zak 2011). Plant growth is increased by CO_2, but gross plant respiration is also stimulated (Leakey et al., 2009). Root growth and the incorporation of organic material below ground are observed in response to elevated CO_2 but so too is enhanced soil respiration fueled by releases of carbon from root systems (Drake et al., 2011; Hoosbeek et al., 2007; Jackson et al., 2009; Lagomarsino et al., 2013; Selsted et al., 2012). Increased carbon supply from plants can lead to enhanced activity of soil fauna and more rapid cycling of carbon, rather than increased carbon storage in soils (Phillips et al., 2012; van Groenigen et al., 2011, 2014). Observed changes in soil carbon were small over the timescale of the FACE studies (3 to 16 years), and thus firm conclusions remain elusive (Luo et al., 2011). In general, large effects of rising CO_2 on carbon storage in soils are not expected (Schlesinger and Lichter 2001).

The long-term effects of rising CO_2 are uncertain because there is only one whole-ecosystem study (i.e., of a salt marsh) that extends to 20 years. Instantaneous physiological responses to CO_2 (Farquhar et al., 1980) typically are modified by feedbacks in system-level studies (Leakey et al., 2009; Norby and Zak 2011). Long-term records from tree-ring analyses are limited to reconstructions of aboveground growth. These studies rarely account for changes in carbon allocation strategies (DeLucia et al., 2005; Norby et al., 2010) caused by rising CO_2 or changes in nutrient limitation (Finzi et al., 2006; McCarthy et al., 2010; Zhu et al., 2016) or belowground carbon storage (Drake et al., 2011; Phillips et al., 2012; van Groenigen et al., 2014).

Summary sentence or paragraph that integrates the above information

While CO_2 is rising globally, there is high confidence that its effects on terrestrial ecosystems will vary across spatial scales because the effects of CO_2 on plants vary by species and may be altered by nutrient and water availability. The long-term impacts of rising CO_2 on carbon storage in terrestrial ecosystems are uncertain.

KEY FINDING 3

Consequences of rising atmospheric CO_2 are expected to include difficult-to-predict changes in the ecosystem services that terrestrial and oceanic systems provide to humans. For instance, ocean acidification resulting from rising CO_2 has decreased the supply of larvae that sustains commercial shellfish production in the northwestern United States. In addition, CO_2 fertilization (increases) plus warming (decreases) are changing terrestrial crop yields (*high confidence, likely*).

Description of evidence base

Commercial oyster larvae in the U.S. Pacific Northwest were significantly damaged by ocean acidification, which caused much higher than usual larval mortality for several years in the

mid-2000s (Barton et al., 2015). Harmful impacts on oysters by ocean acidification were well documented (e.g., Kroeker et al., 2013, and references therein). Crop production increased in response to experimentally elevated CO_2 (Leakey et al., 2009), accompanied by decreases in seed quality. Decreased protein content has been documented in wheat, barley, rice, potatoes, and soybeans grown at high CO_2 (Myers et al., 2014; Taub et al., 2008). Physiological changes also led to increased herbivory in some crops (DeLucia et al., 2012; Dermody et al., 2008). Additional effects are expected for human populations via changes in ocean services, as reviewed in Pörtner et al. (2014). Gattuso et al. (2015) completed a literature review, plus expert judgement assessment, to determine the risk that ocean ecosystem services face from the combined effects of ocean acidification and warming.

Major uncertainties

Uncertainty is related to how rising CO_2 may have affected an array of marine and terrestrial harvests and how they may be affected in the future. Evaluating ecosystem services is difficult, and forecasting changes to these services is even more challenging.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Very high confidence in the existence and attribution of impacts to increased atmospheric CO_2; medium confidence about future projected impacts on ecosystem services.

Estimated likelihood of impact or consequence, including short description of basis of estimate

Studies have already documented impacts to marine and terrestrial harvests. Whether rising CO_2 will affect all marine and terrestrial harvests is uncertain.

Summary sentence or paragraph that integrates the above information

Rising CO_2 has affected commercial shellfish stocks (very high confidence) and changed crop production yields (very high confidence). Additional consequences expected for human populations include more changes to ecosystem services or changes to benefits that terrestrial and oceanic systems provide to humans (medium confidence). Uncertainty centers around the difficulty of evaluating all exploited species and all ecosystem services and projecting potential future impacts on all of them.

KEY FINDING 4

Continued persistence of uptake of carbon by the land and ocean is uncertain. Climate and environmental changes create complex feedbacks to the carbon cycle; how these feedbacks modulate future effects of rising CO_2 on carbon sinks is unclear. There are several mechanisms that would reduce the ability of land and ocean sinks to continue taking up a large proportion of rising CO_2 (*very high confidence*).

Description of evidence base

Acidification varies depending on latitude because CO_2 solubility depends on temperature, with lower-temperature waters holding more CO_2. Polar ecosystems may become undersaturated with calcium carbonate (Ca_3O^{2-}) minerals in the near future (Orr et al., 2005; Steinacher et al., 2010) because of the large amount of CO_2 already dissolved in cold high-latitude ocean areas. Even though low-latitude ocean areas will not become corrosive to Ca_3O^{2-} minerals in the future,

conditions will soon surpass the bounds of natural variability (see Figure 17.4, p. 697). In some places, conditions have already done so (Sutton et al., 2016), exposing low-latitude organisms, such as warm-water coral reefs, to chemical conditions that are considered suboptimal in regard to growth and calcification (Fabricius et al., 2011).

On land, the direct effect of rising CO_2 on plant photosynthesis and growth interacts with rising temperature (Gray et al., 2016; Zhu et al., 2016). Rising CO_2 increases the photosynthetic temperature optimum (Long 1991) because of the decreasing relative solubility of CO_2 versus oxygen at higher temperatures (Jordan and Ogren 1984). Although the sensitivities of photosynthesis, respiration, and decomposition to temperature act on short timescales of decades, chemical weathering sensitivities act over several hundred thousand years and are largely responsible for moderating CO_2 levels throughout the geological record. Higher temperatures affect biogeochemical processes through 1) enhanced NPP; 2) faster microbial decomposition of organic matter involving increased emissions of CO_2 from microbial respiration in soils; and 3) increased rates of chemical weathering, which consumes CO_2 from the atmosphere (Galloway et al., 2014). However, interactions between rising CO_2 and temperatures are complicated by nonuniform climate warming patterns, and research shows that this warming can either stimulate or suppress productivity depending on the season and region (Xia et al., 2014). Higher temperatures and drought have been implicated in widespread tree mortality (Breshears et al., 2009; Allen et al., 2010, 2015), and increased aridity in recent years has had a substantially negative effect on forest growth (Allen et al., 2015); these effects are expected to continue (Ficklin and Novick 2017). While some amelioration of physiological stress might be caused by rising CO_2 (Ainsworth and Rogers 2007; Blum 2009; Morison et al., 2008), extreme droughts may reduce or eliminate these benefits (Gray et al., 2016). There are very few experiments on tree mortality, but no evidence was found that elevated CO_2 reduced drought mortality (Duan et al., 2014).

In the ocean, higher temperatures affect the carbon cycle by decreasing CO_2 solubility in seawater (Zeebe and Wolf-Gladrow 2001); a warmer ocean will hold less carbon. Also, increased surface ocean stratification from the warmer water will prevent CO_2 absorbed by the surface ocean from penetrating into deeper water masses by reducing deep mixing, thereby decreasing overall oceanic carbon uptake and storage (IPCC 2013). In the cryosphere, higher temperatures thaw permafrost and melt ice, processes which release CO_2 and methane (CH_4) from microbial respiration back into the atmosphere (Schneider von Deimling et al., 2012).

Rising temperatures thus influence the response of the carbon cycle to rising CO_2 in diverse and complicated ways, yielding both positive and negative feedbacks to atmospheric CO_2 (Deryng et al., 2016; Dieleman et al., 2012; Holding et al., 2015). Overall, higher temperatures tend to release land and ocean carbon into the atmosphere, while rising CO_2 is projected to increase land and ocean uptake (Friedlingstein et al., 2006), but magnitudes are variable and uncertain. Earth System Model assessments that include carbon cycle feedbacks to climate change show that the combined effects of environmental change yield an overall increase in CO_2 concentrations and thus would likely contribute to more climate warming. The multimodel average CO_2 concentration in 2100 is 985 ± 97 ppm, compared to a concentration of 936 ppm in models lacking carbon cycle feedbacks (Collins et al., 2013). This feedback is highly uncertain because of its dependence on a variety of factors, and thus studies arrive at large ranges in responses (Blok et al., 2010; Elberling et al., 2013; Hodgkins et al., 2014; McCalley et al., 2014; Schneider von Deimling et al., 2012;

Schuur et al., 2009). Temperature also indirectly influences CO_2 radiative effects. For example, enhanced evaporation from the ocean in a warmer world yields higher atmospheric water vapor concentrations that further amplify the impact of CO_2 on climate warming (Myhre et al., 2013).

Major uncertainties

The source or sink status of coastal zones has been difficult to determine, but evidence points to weakening CO_2 release from low-latitude coastal zones and strengthening CO_2 uptake from mid- and high-latitude systems, leading to greater release of dissolved inorganic carbon to the ocean (Cai 2011).

The effect of rising CO_2 on succession and biodiversity remains poorly understood and quantified and could result in changed ecosystem function and different ecosystem services. This lack of understanding also limits the ability to anticipate recovery from acute disturbances such as storms, fires, disease, or insect outbreaks.

Disentangling the impacts of rising CO_2 and other concurrent changes in climate, land use, nutrient cycles, and atmospheric chemistry across all ecosystems probably will require long-term, sustained carbon cycle observations and monitoring of ecosystem and socioeconomic consequences. Long-term observing networks are critical to managing ecosystems sustainably and adaptively (e.g., Schindler and Hilborn 2015), and a focus on data management and interoperability across data platforms would improve understanding of long-term responses to rising CO_2 (Ciais et al., 2014). Few experiments on land or in the ocean extend to a decade, and the balance of conclusions from observational studies is not settled.

Summary sentence or paragraph that integrates the above information

Both oceanic and terrestrial ecosystems are influenced by CO_2 and a variety of environmental controls, including temperature. The effects of climate and CO_2 are likely to interact with each other (i.e., the effect of changing CO_2 depends on the climatic conditions). These interactions likely will cause complex feedbacks to climate.

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18 Carbon Cycle Science in Support of Decision Making

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KEY FINDINGS

1. Co-production of knowledge via engagement and collaboration between stakeholder communities and scientific communities can improve the usefulness of scientific results by decision makers (*high confidence*).
2. Integrating data on human drivers of the carbon cycle into Earth system and ecosystem models improves representation of carbon-climate feedbacks and increases the usefulness of model output to decision makers (*high confidence*).
3. Attribution, accounting, and projections of carbon cycle fluxes increase the usefulness of carbon cycle science for decision-making purposes (*very high confidence*).
4. Developing stronger linkages among research disciplines for Earth system processes, carbon management, and carbon prediction, with a focus on consistent and scalable datasets as model inputs, will improve joint representation of natural and managed systems needed for decision making (*high confidence*).

18.1 Introduction

Recent decades have seen continually increased interest in how best to reduce net carbon emissions, including maintaining or augmenting natural and managed carbon stocks (Griscom et al., 2017) and decreasing anthropogenic carbon emissions. Decisions about carbon management extend from future energy production and technology planning to designs for urban infrastructure and refurbishment; transportation; and agriculture, forest, and natural resource management. Over this same time period, scientists have conducted extensive basic and applied research on biogeochemical cycles, land-cover change, watershed to Earth System Modeling, climate change, and energy efficiency, all of which inform the understanding of the efficacy of various carbon management options (CCSP 2007). However, the information needs of decision makers differ from the objectives that drive basic science to understand natural carbon cycling. Explicitly identifying the information that various decision makers will use, including the form in which they need it, is critical for taking carbon cycle science from laboratory to management action. While much progress has been made in understanding individual components of both fundamental and applied science contributing to decision-making frameworks (see Figure 18.1, p. 730), additional work is needed to connect these components to address existing research and policy questions.

Methods for connecting and integrating basic and applied carbon cycle research take a number of forms. For example, researchers can 1) simplify complex models to provide mean estimates for given activities (e.g., a complex nitrogen cycle model providing mean and uncertainty estimates for nitrous oxide [N_2O] emissions); 2) interpret biogeochemical model results to estimate net carbon flux associated with particular activities (e.g., natural disturbance contributions to global carbon fluxes versus net emissions associated with the management of natural disturbances); or 3) aggregate and analyze scientific data in a different manner to address specific questions (e.g., national emissions estimates versus attribution of net emissions associated with particular activities). These approaches to connect basic science and decision making have most often been employed post hoc, harvesting results from foundational research that already has been conducted to inform decisions, rather than designing and organizing large research programs around user-defined information needs (Lemos and Morehouse 2005). Post hoc methods often are used to synthesize, and sometimes simplify, fundamental research findings for common applications and

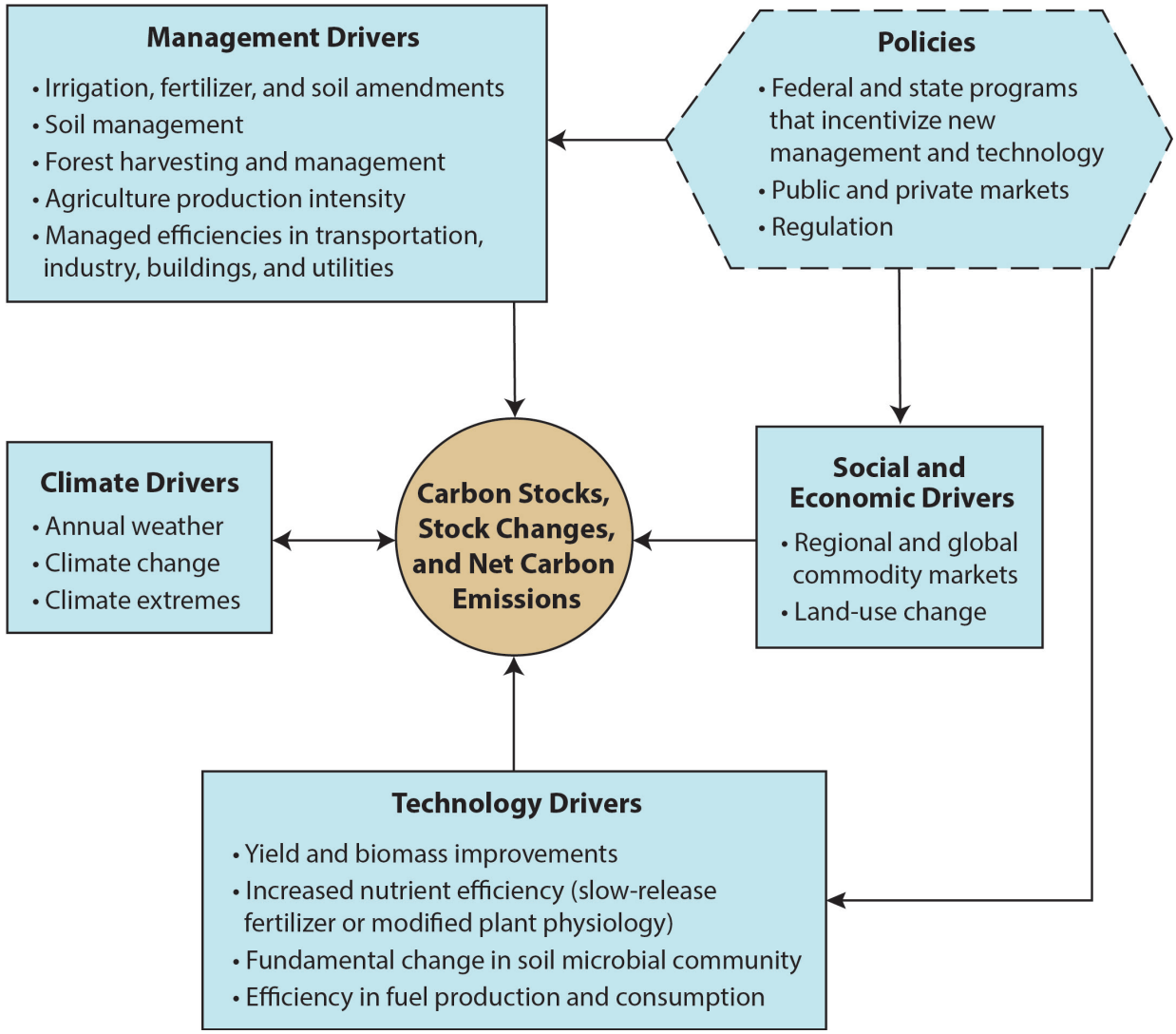

Figure 18.1. Primary Drivers of Carbon Stocks and Emissions. Carbon and carbon dioxide (CO_2) estimates can be generated using observations, models of differing complexity, or both. To understand and estimate future carbon stocks and emissions, drivers of carbon stock changes and carbon emissions must be considered and represented. This schematic illustrates examples of components needed to represent carbon stock changes prior to addressing policy drivers.

decision making, including in the Intergovernmental Panel on Climate Change's (IPCC) *2006 Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) and the U.S. Department of Agriculture's (USDA) *Methods for Entity-Scale Inventory* (USDA 2014).

While organizations make decisions with whatever information they have available, multiple, competing interests are generally at play in setting priorities, so the quality and credibility of information can influence decisions about carbon management. Some decisions about carbon cycle management require only coarse-level estimates or discipline-specific knowledge, while others benefit from more nuanced analysis or multidisciplinary research. Multidisciplinary research is particularly

needed to inform economy-wide carbon management targets (e.g., to maintain atmospheric carbon dioxide [CO_2] within a safe operating space for humanity; Rockstrom et al., 2009) and to understand links among sectors (e.g., soil carbon in the land sector associated with biofuel production in the energy sector). Collaborations between scientists and practitioners increase the chances that information intended to inform decisions is actually needed and delivered in a highly useful manner. For decisions affecting multiple sectors, collaborations among scientists of many disciplines tend to produce knowledge that is more credible and practical in the eyes of multiple stakeholders compared to knowledge produced in more siloed environments (Weaver et al., 2014). Although collaborations have increased (Mooney et al., 2013), there remain lost opportunities for effective carbon cycle management that could be captured via more integration.

Federal, state, and local policymakers; company executives; energy managers; urban designers; natural resource managers; families; and individuals make short- and long-term decisions that can influence the carbon cycle. These entities require adequate information from science-based analyses to inform their choices and to understand how management, technologies, or behavioral decisions can affect net carbon emissions or carbon stock changes. Meanwhile, scientists are developing more sophisticated monitoring, data interpretation, and modeling methods that could be relevant to these decision makers, providing more refined understanding. An important but challenging part of carbon cycle science is ensuring that scientists have sufficient understanding of decision makers' needs to produce information that actually is usable by decision makers and that funding organizations place sufficient priority on actionable science. To facilitate strategic, effective use of carbon cycle science in carbon management, as well as to provide insights about the opportunities and constraints that shape the availability of user-driven carbon cycle science now and in the future, this chapter provides information on national and international needs for carbon cycle information, current status of research to inform carbon cycle and greenhouse gas (GHG) management, and future needs. It also focuses on the sectors of agriculture, forestry, and other land uses (AFOLU) and discusses energy and associated carbon sources in the context of integrated carbon cycle systems.

18.2 User Demand for Carbon Cycle Science

Diverse institutions demand information about the carbon cycle that enables them to meet their particular objectives and interests. For example, stakeholders wishing to prioritize actions for reducing emissions need to know the distribution among sectors (e.g., transportation, infrastructure, buildings, power generation, and land management), as well as the technical, economic, and behavioral potential for reducing these emissions in different sectors and locations. Illustrative questions that stakeholders including decision makers ask include:

1. How much can emissions be reduced from transportation versus power generation versus building sectors, and at what costs?

2. What actions are consumers likely to take, and which kinds of technologies (e.g., smart meters) and campaigns (e.g., foot-in-the-door models) are likely to result in behavioral change (Scott 1977; Mogles et al., 2017)?

3. How much methane (CH_4) leaks into the atmosphere from natural gas wells and pipelines, and how does that leakage influence the attractiveness of natural gas as a "bridge" fuel (Miller et al., 2013)?

4. How can carbon be managed from procurement through production and inventory management (Benjaafar et al., 2013)?

5. How fast will different agricultural practices build soil carbon or reduce CH_4 emissions from cattle, and how will these rates vary geographically (Olander et al., 2014)?

6. How will the consequences of different sets of agricultural and forest management practices on a single tract of land add up?

18.2.1 Variety in Types of Users and Their Needs

Users of carbon cycle science to reduce emissions include 1) carbon registries and protocol developers (Gonzalez 2014; Climate Action Reserve 2018), 2) businesses that have made voluntary commitments to reducing GHG emissions from their supply chains (Christopher 2011; Tseng and Hung 2014; CISCO 2017; Walmart 2017), 3) utilities developing strategies for reducing their GHG footprints (Consolidated Edison 2016), 4) state and municipal governments committed to reducing GHG emissions in their public and private sectors (Carbon Neutral Cities Alliance 2018; Elizondo et al., 2017), and 5) non-governmental organizations and research institutes producing roadmaps to achieve different atmospheric CO_2 targets (UCS 2009). In addition, national governments and international organizations rely on carbon cycle science combined with policy and management practices to identify the primary socioeconomic drivers of carbon emissions (e.g., Fricko et al., 2017; Rogelj et al., 2018) and to understand how well science-based recommendations for carbon budgets align with global commitments for carbon management (Fricko et al., 2017; Burke et al., 2018; Rogelj et al., 2018). These users vary in the types of decisions they make about carbon cycle management; their capacity to support research or engage with research institutions; their maturity in defining their information needs; and their potential to impact regional, national, or global carbon pools. Mapping these capacities with an eye toward producing information in formats that align with standard business practices would be a valuable contribution for social science research.

18.2.2 Institutional Arrangements for Meeting User Demand

Despite having identified numerous users of carbon cycle science and the deep knowledgebase summarized within this report, tailoring and synthesizing carbon cycle science to make it truly useful to specific institutions continue to present a challenge. In carbon management, as in numerous other realms of decision making that benefit from technical input, the traditional science supply paradigm for producing usable or socially robust knowledge (i.e., provide the research results, and somebody will eventually use them) remains problematic and usually ineffective. The disconnect between knowledge production and consumption is particularly apparent when applying cross-disciplinary research to societies (Dilling 2007). In contrast, various initiatives have demonstrated that beginning research by identifying user information demands, subsequently working intensively with users to understand those needs in detail, ultimately leads to science products that are actually used (Zell et al., 2012). User-driven science, however, thrives when institutions shift their priorities to meet user needs and set reward structures accordingly.

Co-Production of Knowledge

The hybrid approach that has enabled user demand to take advantage of carbon cycle science within the confines of existing institutional structures has been referred to as the co-production of knowledge by scientists and the user community (Cash et al., 2006; Dilling and Lemos 2011). This coordination entails establishing a shared vision that a decision-making process requires, and ensuring that the decision makers receive information in a usable format and at an appropriate time (Brown and Escobar 2013). In addition to engaging stakeholders, co-production of knowledge also emphasizes collaboration across scientific disciplines. Although cross-disciplinary research has received considerable discussion over the past few decades, institutional cultures within a number of large organizations that have especially robust research capacity continue to impede collaborations in the absence of strong direction and leadership to do otherwise (Mooney et al., 2013; Weaver et al., 2014). Overcoming barriers between the sciences (see McGreavy et al., 2015) remains a challenge to producing information that effectively influences decision making.

Examples of co-production and user-driven research in which carbon cycle science has informed management action include development of the Southeast Florida Regional Climate Change Compact (Georgetown Climate Center 2017), the Maryland Carbon Monitoring System (University of Maryland 2016), and methods for reducing emissions from deforestation and forest degradation plus (REDD+; see Section 18.3.2, p. 736) accounting in Mexico (Birdsey et al., 2013).

Boundary Organizations

Boundary organizations facilitate interactions between science producers and users by helping to structure the flow of information from basic and applied research to decision making, enabling improved engagement and stronger relationships across disciplines (Kirchhoff et al., 2013; see Figure 18.2, this page). They focus on activities that engage all carbon cycle science disciplines and promote opportunities to foster interdisciplinary and intramural collaboration (Clark et al., 2016). Diverse non-governmental organizations have played a strong role engaging with carbon cycle research activities to understand and apply the science. A primary objective of these organizations is to support and present science in ways that enable local and individual action that links science to decision making at a variety of scales.

The North American Carbon Program (NACP) is an example of a boundary program that supports scientists' efforts to engage in social, economic, and policy-relevant research to improve how carbon cycle science is conducted and ensure policy-relevant findings (NACP; Michalak et al., 2011). A co-authorship network analysis using data from publications of core NACP members indicates that the structure and collaborative pathways within the NACP community created an effective boundary organization (Brown et al., 2016). Results illustrate that the NACP community expanded its research on human and social impacts on the carbon cycle, contributing to a better understanding of how human and physical processes interact with one another. NACP has formed a tightly connected community with many social pathways through which knowledge may flow, and it has expanded its network of institutions involved in carbon cycle research over the past several years (Brown et al., 2016). Further coordination of research in social science, economics, business management, and carbon cycle science should enable decision makers to understand the motivations for people's actions that either directly or indirectly affect the carbon cycle (see Ch. 6: Social Science Perspectives on Carbon, p. 264) and the situations in which refined understanding of the biophysical carbon cycle can

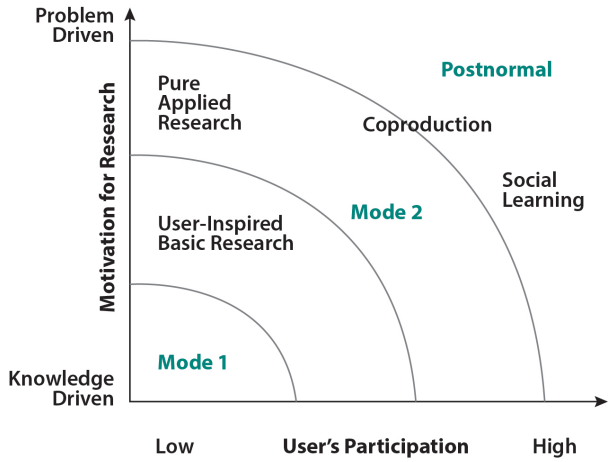

Figure 18.2. Evolution in the Complexity of Knowledge Production and User Participation. On the vertical axis, the complexity of knowledge production increases from low (where production is predominately focused on increasing fundamental knowledge) to high (where production aims to help solve societal problems). On the horizontal axis, the complexity of user participation changes from low to high as users become increasingly active in the knowledge-creation process. **Mode 1** represents the concept that societal benefits accrue because of the separation of science from society, where science is separated from society to maintain objectivity and credibility. **Mode 2** organizes science production at increasing levels of interaction and integration across disciplines (from multidisciplinary to transdisciplinary) and across the science-society divide. In **postnormal science**, scientific knowledge alone is not enough to solve societal problems; therefore, interaction between producers and users of science across the science-society interface entails specific involvement of stakeholders throughout the process. [Figure source: Redrawn from Kirchhoff et al., 2013, copyright Annual Reviews (www.annualreviews.org), used with permission.]

influence business decisions such as supplier selection for creating low-carbon supply chains (Hsu et al., 2013).

18.3 Carbon Cycle Science Used for Decision Making

Carbon cycle science supports decisions in a number of national and international contexts. For example, decisions about managing ecosystems such as national or state forests require integrating stakeholder perspectives with scientific input on the consequences or alternative policy approaches for ecosystems, emissions, and climate (BLM 2016). At the international level, as countries establish goals to stabilize carbon and GHG concentrations in the atmosphere, the scientific community should play an important role in assessing carbon budgets and developing the technologies, methods, and practices for reducing net GHG emissions and managing carbon stocks. Global efforts to slow deforestation, improve human health, and decrease global GHG emissions will be aided by substantial input from the international scientific community and respective national agencies. In all of these examples, and many others, improvements in the quality and process of scientific input can help inform sound decision making. Recent research on CH_4 emissions provides a notable example of fundamental carbon cycle science used in decision making. Reducing anthropogenic CH_4 emissions has become a high priority for policymakers, given the potential for near-term climate benefits and the relative tractability[1] of monitoring and mitigating emissions from many sectors. Concerted effort to develop relationships among scientists and decision makers has enabled progress in identifying information needs, developing technology to provide needed information, and establishing science questions that evaluate existing knowledge. With respect to policy drivers, new laws and rules have been enacted to mitigate and measure CH_4 emissions in California and other key regions and sectors in the United States (Federal Register 2016a, 2016b). Atmospheric or "top-down" scientific methods for detecting, quantifying, and attributing CH_4 fluxes have dramatically improved. For example, satellite observations have enabled scientists to identify concentrated regions of CH_4 emissions, information relevant to policy and management that previously had not been well known or understood (Kort et al., 2014). Recent field studies have revealed evidence of a long-tail statistical distribution of emissions sources in the U.S. natural gas supply chain, where a relatively small number of superemitters dominate key regions and sectors (Brandt et al., 2014; Zavala-Araiza et al., 2015; Zimmerle et al., 2015). Some stakeholders (e.g., California Air Resources Board) already have applied the atmospheric and field research findings to make corrections to CH_4 inventory estimates. Additionally, recent advances in remote sensing of CH_4 point sources (Frankenberg et al., 2016; Thompson et al., 2016) demonstrate the potential to efficiently detect leaks from point sources.

Because the demand for tailored knowledge is often urgent, specific, and only weakly aligned with incentives that drive fundamental research, consulting firms and non-governmental organizations (NGOs) have often met this demand. These institutions have generated a great deal of user-driven science over the decades. For example, the World Wildlife Fund (WWF) and the Carbon Disclosure Project (CDP) partnered with multiple, large, U.S.-based corporations to produce *The 3% Solution*, an analysis of the business case for businesses to achieve net savings of up to $190 billion by 2020 through measures to reduce carbon emissions (WWF and CDP 2013). Woods Hole Research Center, in collaboration with the U.S. Agency for International Development (USAID), produced a map of aboveground carbon stocks in Mexico. The map built on information already assembled by Mexico's government for its

[1] Mitigation of methane (CH_4) emissions—particularly point sources from the energy, waste, and some agricultural sectors—has strong near-term tractability because it involves detecting and repairing local fugitive emissions rather than economy-wide shifts in energy and transportation infrastructure associated with fossil fuel carbon dioxide (CO_2) mitigation. Monitoring anthropogenic CH_4 fluxes is generally more tractable (with existing technology) than monitoring CO_2 fluxes, since the latter includes large, confounding fluxes from the biosphere. However, area sources of CH_4 such as wetlands and some agricultural fluxes (e.g., rice and enteric livestock emissions) continue to present a challenge.

National Forest Inventory and met a clear need to advance the estimates of Mexico's forest carbon stocks at both national and municipal levels (Cartus et al., 2014; WHRC 2014). As these examples illustrate, contract-driven science is sometimes made publicly available, such as when governmental agencies provide funding to support projects in the public interest or when private-sector entities and NGOs partner to develop analyses of common interest. However, the private contract model has limitations. Many products of contract research remain outside the public domain, and users without the resources to purchase these goods cannot easily access tailored information for their decision-making needs. User institutions that lack these resources are typically smaller and also have less influence than their larger counterparts in a variety of forums. This imbalance in access to information has profound implications because, as many chapters in this report demonstrate, carbon management has consequences for all of society, not only the entity making a particular decision. Because user-driven science that does not enter the public domain is difficult to access, further characterization of its contributions or extent are not included in this chapter. In spite of this, significant effort should be placed on accessing relevant science that is outside the public domain in order to determine whether this science has sufficient value to impact the decision-making process.

18.3.1. Use of Carbon Cycle Science for Land Management

The carbon research community performed a great deal of work in the past decade with the aim of improving decision making in agriculture, energy production and consumption, building infrastructure design and maintenance, transportation, and many other sectors that consume fossil fuels or generate land-based emissions. This research filled knowledge gaps that helped decision makers understand multiple impacts of land-management decisions. Research foci included, for example, ecosystem disturbance (e.g., fire and pest outbreaks), human health and risk, indirect land-use change, efficient production throughout commodity supply chains, full life cycle energy and emissions impacts of ecosystems and production systems, and how these analyses change under alternative land-management scenarios. Federal guidance to U.S. agencies documents how full GHG accounting has been incorporated into environmental impact analyses under current and alternative scenarios (Federal Register 2016b). Briefly illustrated here is the potential impact of scientific input on land management through examples of land-use policy and of terrestrial management on the carbon cycle.

The use of carbon cycle science for decisions on carbon emissions reductions in agriculture is relevant for a wide suite of societal and policy questions relating to the direct impacts of land-use decisions on energy, emissions, health, and ecosystems (see Ch. 5: Agriculture, p. 229). For example, carbon cycle science from multiple disciplines informs dialogue and decisions about the role biofuels can play in the energy economy. Biofuels can include dedicated energy crops, agricultural wastes and residues, and CH_4 from agricultural wastes. The use of biofuels can decrease GHG emissions, depending on net changes in biomass growth stocks across the landscape (e.g., harvest rates, deforestation, and indirect land-use change) and on the net efficiency of converting biomass to energy (see Ch. 3: Energy Systems, p. 110). Biofuel policy options have complex and highly variable implications for carbon emissions that are a function of energy expended in production, processing, and use of biofuels; indirect land-use change; and ecological and economic costs and benefits of biofuels (Paustian et al., 2001). In seeking solutions to energy, environmental, and food challenges, biofuels can either contribute positively or negatively to existing societal issues (Tilman et al., 2009). Full carbon cycle analysis and modeling are key to ensuring that policies and resulting actions actually lower carbon emissions instead of raising them. Such analyses continue to be used to ascertain the benefit of biomass to reduce net emissions, including biomass burning (Cherubini et al., 2011; Johnson 2009; Khanna and Crago 2012; Miner et al., 2014; Mitchell et al., 2012; Tian et al., 2018) and forest thinning to reduce

wildfire risks (Campbell et al., 2012; Mitchell et al., 2009). Analyses at different spatial scales (e.g., plot, national, and global) and temporal scales (e.g., years, decades, and centuries) can yield different conclusions for land-related carbon issues, indicating the need to synthesize or integrate approaches used across scales (i.e., plant growth models, land-use change models, integrated assessment models (IAMs), and natural resource supply models).

18.3.2 Carbon Management Strategies

While some carbon management strategies are still being debated within the science community, a number of strategies have been well documented and quantified. Some of them are summarized from results in preceding chapters of this report (see Table 18.1, p. 737). Many land-based strategies are associated with changes in management. Humans have a long history of altering the landscape and associated carbon stocks around the world since initial settlement and population expansion (Sanderman et al., 2017; Köhl et al., 2015). People have changed forests to agricultural areas and vice versa; changed management of soils, forests, grasslands, and other ecosystems; and developed urban and suburban areas. There is a robust literature of observations and carbon stock comparisons under different land uses and management regimes that provides guidance for managing natural resources, fossil resources, and renewables with regard to carbon. Potential sequestration rates have been estimated by aggregating data from hundreds of paired plots, and the data have been used for national scale estimates (U.S. EPA 2016) and global default values for numerous management practices across land, energy, and transportation sectors (IPCC 2006). Research has moved beyond estimating the influence of management changes within a sector, to evaluating how change in one land or energy sector causes changes in other land or energy sectors.

The many land-management options available to reduce net GHG emissions or increase removal of GHGs from the atmosphere (see Table 18.1), taken together, could reduce net emissions by 100 to 500 teragrams of carbon (Tg C) per year, with co-effects becoming highly significant in the high end of this range. Therefore, decisions about land-management policies must take into account the co-effects, which may be positive or negative, along with the potential benefits in terms of reducing GHGs. One of the most significant negative impacts of altering land management to increase carbon storage is a potential reduction in land area devoted to food production if the amount of additional land required exceeds the area of "marginal" (i.e., not productive for crops) land available. On the other hand, positive co-effects may result from management practices that increase soil fertility along with carbon storage, or those that increase protection of water quality or damage from storms and floods.

Although traditionally considered the province of biophysical science, the demand for actionable results has increasingly drawn attention to the need for research from sociology, psychology, and human behavior to inform carbon management. Research in these fields has identified obstacles to effective carbon management, and the approaches to overcome them, at individual to institutional scales (Ross et al., 2016). In researching the interests and understandings held by different actors in Mexico's program for monitoring, reporting, and verifying (MRV) REDD+, Deschamps Ramírez and Larson (2017) found tension arising from poor understanding of international reporting requirements and the roles and responsibilities of subnational institutions. Weaknesses in understanding and social relations among key institutions limit the effectiveness of carbon management even when decision makers possess and understand strong biophysical analyses (Deschamps Ramírez and Larson 2017). Individuals respond strongly to default options and associated social norms, as demonstrated in comparisons of decisions about whether or not to participate in organ donor programs among different countries. Default settings on furnaces and other appliances to conserve energy, with the option for owners or users to change that setting, could produce widespread behavior shifts and associated changes in carbon emissions (Ross et al., 2016). Efforts to support the capacity of businesses to manage carbon involves research but

Table 18.1. Summary of Options, Capacity, and Co-Effects for Reducing Greenhouse Gases (GHGs) in North America[a]

Activity	Impact on GHGs	Potential Reduction[b]	Co-Effects
Afforestation and improved forest management (Ch. 9, 12)[c]	Increase in net removals from the atmosphere. Reduction in emissions by avoiding the conversion of forests and grasslands to other cover types. Increase in carbon removals from the atmosphere by promoting the conversion of other land covers to forests or grasslands.	30 to 330 teragrams of carbon (Tg C) per year (U.S. only)	Potential impacts on food production, biodiversity, net forest resources, and counter harvesting elsewhere (i.e., leakage), resulting from increased forestland area.
Managing grasslands (Ch. 10)[c]	Increase in net removals from the atmosphere and in biomass and soil carbon storage by improving grazing practices and grasslands management.	Tens of Tg C per year (U.S. only)	Shifts in species composition.
Reducing methane (CH_4) emissions from livestock (Ch. 5)[c]	Reduction in net agriculture emissions by controlling livestock CH_4 emissions.	13 to 19 Tg C per year	Potential co-benefits such as improved feed efficiency or productivity in livestock.
Cropland management practices (Ch. 5, 12)[c]	Increase in organic residue inputs and soil carbon stocks by reducing tillage and summer fallow, implementing cover cropping, or managing nutrients to increase plant production. Reduction in CH_4 and nitrous oxide (N_2O) emissions by optimizing nitrogen fertilization and water management.	Soil carbon stock increases of up to 3 megagrams of carbon per hectare; up to 80% reduction in CH_4 (especially rice) and N_2O, depending on crop, environment, and combination of practices.	Potential co-benefits such as improved soil productivity and lower costs for nitrogen fertilizers. Increased organic carbon for improved buffering capacity, water holding capacity, soil fertility, and tilth. Reduced water use (especially rice).
Reducing wetland and coastal ecosystem loss (Ch. 13, 15)[c]	Reduction in emissions by avoiding the loss of wetlands and coastal estuaries. Increase in carbon sequestration by restoring drained wetlands, though possibly increasing CH_4 emissions.	Based on the amount of wetlands converted to other land uses in Canada and the United States, restoring all wetland acreage, leading to a gross but highly unrealistic estimate of 43 Tg C per year.	Potential impacts on coastal zone development. Increased protection of property from storms. Reduced export of nutrients to the ocean. Restored wetlands via improved flood abatement and water quality, but with only about 21% functional compared to functionality of undisturbed sites.

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(Continued)

Table 18.1. Summary of Options, Capacity, and Co-Effects for Reducing Greenhouse Gases (GHGs) in North America[a]

Activity	Impact on GHGs	Potential Reduction[b]	Co-Effects
Urban mitigation (Ch. 4)[c]	Reduction in city carbon emissions by implementing or improving urban development pathways, building codes, transportation planning, electricity supply, or biotic planning (e.g., tree planting). Reduction in CH_4 leakage, for example, by upgrading infrastructure.	Data unavailable for a comprehensive assessment of mitigation potential.	Implications for air quality, urban heat island, and human health, among the many co-effects and priorities for consideration.
Increasing bioenergy (Ch. 3)[c]	Possible reduction or increase in net GHG emissions by substituting biofuel for fossil fuel. Impacts dependent on fuel source and effects on production and consumption cycles.	Estimates of mitigation potential based on life cycle analysis unavailable, though biofuel supply is potentially large.	Increased agricultural commodity prices and land-use changes in other regions, dependent on extent of land supplying the biofuel. Increased forest harvesting in response to higher demands for forest biomass, possibly followed by forest area expansion.

Notes

a) Table includes GHG emissions reductions, carbon stock increases, and avoidance of carbon losses.

b) Potential reductions are in addition to baseline.

c) Chapter titles—3: Energy Systems, p. 110; 4: Understanding Urban Carbon Fluxes, p. 189; 5: Agriculture, p. 229; 9: Forests, p. 365; 10: Grasslands, p. 399; 12: Soils, p. 469; 13: Terrestrial Wetlands, p. 507; 15: Tidal Wetlands and Estuaries, p. 596.

can fall outside traditional academic frameworks. For example, the Sustainable Purchasing Leadership Council (SPLC) evaluated third-party tools for estimating supplier sustainability across an entire supply base (SPLC 2018). Although these tools focus more broadly than carbon, SPLC's work summarizing and evaluating them demonstrates the type of collaboration that spurs user-driven science and produces actionable recommendations.

18.4 Technical Capabilities and Challenges for Supporting Decision Making

Assuming adequate organization, communication, and funding is in place, there are a number of scientific and technical challenges associated with better connecting basic and applied science for decision-making purposes. This section discusses current capabilities and needs for data, modeling, accounting, and broad system approaches for carbon management.

18.4.1 Data Collection, Synthesis, and Analysis

Data for basic carbon research and decision making are often similar, although they typically are used independently instead of informing one another. For example, global climate models rely on national and global datasets on human activities and land management. Conversely, models of natural resource ecosystems and economics that inform land

management require input on global changes in total land resources, commodity markets, and climate. A revised assessment of existing data, across disciplines, could help basic and use-inspired research on carbon and also address interrelated climate and carbon research issues.

Inventory data on fossil fuel emissions and land emissions and sinks are estimated nationally (e.g., U.S. EPA 2016) and reported internationally under the United Nations Framework Convention on Climate Change (UNFCCC). Advances in carbon cycle science are reflected in carbon modeling and accounting used to produce the inventory data. For example, field experiments that collect data on fertilizer application methods and timing, livestock and manure management, soil management, and other activities can be incorporated into models that estimate GHG emissions, thereby refining the national carbon budget.

Inventory data provide information on emissions sources and sinks and how net emissions change with land management or fuel supplies. To be most useful for local and regional planning, these data often require spatial distribution (West et al., 2014) or additional information on land-cover, land-use, and ecosystem characteristics that may be provided by satellite remote-sensing or economic survey data. Integrating inventory and remote-sensing data can provide new data products to understand local and regional carbon dynamics (Huang et al., 2015) and to inform land-management and policy decisions. Using integrated data on land use and management in climate modeling activities may become increasingly important (Hurtt et al., 2011) to facilitate consideration of climate feedbacks in local and regional decision making.

Although inventory data often serve as the basis for understanding human-induced impacts on the carbon cycle and subsequent decision making on carbon mitigation strategies, other datasets can provide additional or complementary estimates. For example, fossil fuel emissions can be estimated by the production of fossil fuels (U.S. EPA 2016) or by the consumption of fossil fuels (Patarasuk et al., 2016). The same is true for land-based emissions, which can be estimated using ground-level survey data from the Forest Inventory Analysis or the National Agricultural Statistics Service (West et al., 2011) or using atmospheric concentration data and modeled with atmospheric transport and inversion models (Schuh et al., 2013). The survey or inventory data represent "bottom-up" estimates while the atmospheric data represent a "top-down" approach. Reconciling data and approaches benefits both basic and applied science. Earth System Models (ESMs) require accurate base-level data and also need multiple ways to evaluate results. Similarly, inventory data used in models for decision making could benefit from alternative estimation approaches that evaluate existing inventory estimates (Jacob et al., 2016). Also needed are continued development and reconciling of data collection and modeling approaches to estimate carbon stocks and fluxes, requiring coordination among researchers, decision makers, and funding sources (see Box 18.1, Key Data Needs for Decision Making on Terrestrial Carbon, p. 740).

18.4.2 Decision Support Tools for Carbon and Greenhouse Gas Management

Research models and decision support tools that can forecast future changes, as well as integrate and analyze current and past conditions, can provide solutions to challenges presented by climate change. At the broadest level, capabilities include assessment and decision-making tools that analyze feedbacks between human activities and the global carbon cycle. These capabilities can enable decision makers to 1) assess how changes in the carbon cycle will affect human activities and the ecosystems on which they depend and 2) evaluate how human activities—past, present, and future—impact the carbon cycle.

National GHG Inventories Critical for Modeling

For national-scale planning and in international agreements and negotiations, national GHG inventories have consistently been recognized as essential parts of the model-data system. Policy developments of the past few years have reinforced the global

Box 18.1. Key Data Needs for Decision Making on Terrestrial Carbon

- Collect and analyze inventory data that observe and represent changes in carbon stocks associated with human drivers.
- Integrate inventory and remote-sensing data for inclusion in Earth System Models.
- Reconcile different carbon emissions and sink estimates to further improve independent and combined estimates.
- Explore and develop plausible scenarios for the influences of different demographic, social, and geopolitical trends and developments in other sectors (e.g., energy) on terrestrial carbon.
- Refine and decrease uncertainty of estimates for land-based carbon emissions and stock changes.

recognition of the need for high-quality and regularly reported GHG inventories. Increasing numbers of developing (i.e., UNFCCC non-Annex 1) countries produce annual GHG inventories and submit them to the UNFCCC using an extensive set of guidelines for national GHG reporting based on IPCC GHG inventory reporting guidelines (IPCC 1996, 2003, 2006). Deforestation and forest degradation constitute a major source of carbon emissions in many developing countries; the Global Forest Observations Initiative (GFOI) has developed guidance for using remotely sensed and ground-based data for forest monitoring and reporting of reduced emissions from deforestation, forest degradation, and associated activities produced in cooperation with UN-REDD and Forest Carbon Partnership Facility (FCPF) initiatives (http://www.gfoi.org/methods-guidance).

Most GHG inventories rest on estimates of the emissions associated with a particular activity (e.g., amount of CO_2 emitted per amount of fuel combusted). The factors that relate activities to emissions are called emissions factors. For sectors dominated by fossil fuels (e.g., power generation, transportation, and manufacturing), emissions factors are well constrained (IPCC 2006). Therefore, the major limitation to estimating emissions accurately is the ability to collect, organize, and verify the activity data (e.g., numbers of transformers upgraded, hectares of perennial plants established for bioenergy, and number of cattle raised on forage known to reduce CH_4 production). For biogenic-driven GHG emissions, such as those associated with agriculture and forestry, there is much greater variability in the emissions rate per unit of activity (e.g., N_2O emissions per unit of fertilizer added) because of heterogeneity in climate and soil conditions and in management practices. Dynamic process-based models offer an alternative approach that can account for this heterogeneity (Del Grosso et al., 2002; Li 2007), but using these models requires sufficient capacity (e.g., trained staff, functioning institutions).

GHG inventories that use activity data and emissions factors (or activity-specific process modeling) are referred to as bottom-up approaches (see Section 18.4.1, p. 738). All national GHG inventories use this approach, which, by definition, attributes emissions sources and sinks to identifiable entities and activities and lends itself to policy applications to reduce emissions and incentivize sinks. Examples of spatially explicit, high-resolution model-data systems for major source categories include fossil fuel emissions (Gurney et al., 2012; Gurney et al., 2009), forest dynamics (USDA 2015), biofuels (Frank et al., 2011), and land-use change (Sleeter et al., 2012; Woodall et al., 2015). These data combine knowledge of biophysical processes with data on human activities and economics that can help municipalities or geopolitical regions understand and quantify carbon emissions and sinks, thereby informing decision making. Challenges to these bottom-up approaches, aside from improving data quality on both activities and emissions factors to

reduce uncertainties, include ensuring completeness and avoiding double-counting of sources.

Land-Use Emissions Projections and Examples of Sector-Specific Tools

In addition to inventories, the carbon cycle science community develops projections that scale from local mitigation options to global impacts and, conversely, from global economic forces to local strategies. Many countries incorporate land-use emissions into their overall climate targets in some way, and these projections inform national and international strategies to address CO_2 emissions, carbon management options, and other sustainability goals. These estimates of future land-use sources and sinks are useful for decision making because they stem from a reliable, scientifically sound, and transparent process (U.S. Department of State 2016). Because this work reflects the development and use of new approaches in carbon cycle science, further work is widely acknowledged as being helpful to increasing the usefulness of land-use emissions projections.

Models and decision tools have also been designed to help industry, business, or other entities (e.g., universities, land-management agencies, farmers, and ranchers) assess their emissions and develop mitigation strategies. In a regulatory environment where emissions are in some way limited by law, models and decision tools are essential for planning, forecasting, and monitoring emissions reductions. These tools also are widely used in voluntary carbon accounting and reporting to generate and sell carbon credits from a variety of activities (CARB 2018).

Models and decision support tools for inventory and forecasting in the AFOLU sector at the scale of the farm, woodlot, or business have been developed and are increasingly deployed as tools to guide implementation of government-sponsored conservation programs. These tools can help inform decisions to reduce the GHG footprint of agricultural commodities through supply-chain management by agricultural industries and to support agricultural offsets in carbon cap-and-trade systems (see examples below).

- COMET-Farm (cometfarm.nrel.colostate.edu; Paustian et al., 2018)—Helps farmers and other landowners estimate carbon benefits associated with implementing practices supported by conservation programs of the USDA Natural Resources Conservation Service (Eve et al., 2014).
- Cool-Farm Tool (CFT; www.coolfarmtool.org/CoolFarmTool; Hillier et al., 2011)—A product of the Cool Farm Alliance, CFT is designed for use by farmers and is intended to support the Alliance's global mission of enabling millions of growers to make more informed on-farm decisions that reduce their environmental impact.
- DNDC (Denitrification-Decomposition) process-based biogeochemical model (Li 2007)—Used by institutions like the California Air Resources Board to support CH_4 reductions from rice farming as an agricultural GHG offset in California's GHG emissions reduction program (Haya et al., 2016).
- ExACT (Ex-Ante Carbon balance Tool; www.fao.org/tc/exact/ex-act-home/en)—Estimates CO_2 equivalent (CO_2e)[2] emissions based on a project's implementation as compared to a "business-as-usual" scenario. Project designers can use ExACT as a planning tool to help prioritize mitigation-activity terms.
- ALU (Agriculture and Land Use; www.nrel.colostate.edu/projects/ALUsoftware) national GHG inventory software—Assists countries in completing their national inventories. This tool was developed to meet a U.S. governmental priority of increasing the number of countries developing robust GHG inventories to create transparent, evidence-based understanding of global GHG emissions.

[2] Carbon dioxide equivalent (CO_2e): Amount of CO_2 that would produce the same effect on the radiative balance of Earth's climate system as another greenhouse gas, such as methane (CH_4) or nitrous oxide (N_2O), on a 100-year timescale. For comparison to units of carbon, each kg CO_2e is equivalent to 0.273 kg C (0.273 = 1/3.67). See Box P.2, p. 12, in the Preface for details.

- Climate Change, Agriculture, and Food Security–Mitigation Options Tool (CCAFS–MOT; ccafs.cgiar.org/mitigation-option-tool-agriculture)—Identifies practices in Africa, Asia, and Latin America that can reduce emissions and sequester carbon on agricultural lands. MOT prioritizes effective mitigation options for many different crops according to mitigation potential, considering current management practices, climate, and soil characteristics.

- National Oceanic and Atmospheric Administration (NOAA) Annual Greenhouse Gas Index (toolkit.climate.gov/tool/annual-greenhouse-gas-index-aggi)—Compares the total combined warming effects of GHGs (including CO_2, CH_4, N_2O, and chlorofluorocarbons) to their 1990 baseline levels.

- Bioenergy Atlas (toolkit.climate.gov/tool/biofuels-atlas)—Includes maps enabling the comparison of biomass feedstocks, biopower, and biofuels data from the U.S. Department of Energy (DOE), U.S. Environmental Protection Agency (EPA), and USDA. (Software hosted by DOE's National Renewable Energy Laboratory.)

- Global Carbon Atlas (www.globalcarbonatlas.org)—Aggregates global carbon data to explore, visualize, and interpret global and regional carbon information and changes from both human activities and natural processes. (Supported by the Global Carbon Project, www.globalcarbonproject.org; and BNP Paribas.)

Comparable decision support tools for carbon management have been developed for other sectors. For example, USAID's Clean Energy Emissions Reduction (CLEER) tool, based on internationally accepted methodologies, enables users to calculate changes in GHG emissions resulting from adoption of geothermal; wind; hydroelectric and solar energy generation; upgrades of transmission and distribution systems; increases in building energy efficiency; heating, ventilation, and air conditioning system efficiency improvements; fuel switching; capture of stranded natural gas by flaring; use of biomass for energy; and use of anaerobic digesters to capture CH_4 from livestock manure (USAID 2018).

Complex, Multisector Modeling

Integrated Assessment Models merit particular attention because they constitute a distinct field of research and serve a unique role in decision support. Among decision support tools for carbon management, IAMs are unique in estimating economy-wide responses, including GHG emissions, to different management and policy options. The objective of these models is to capture the primary interactions and interdependencies between natural and human systems (e.g., economic sectors) through a series of scenarios that represent plausible policy interventions (Weyent 2017). These models can help understand feedbacks among carbon sources and sinks at national and global scales (see Figure 18.3, p. 743), given specified emissions targets or implementation of carbon strategies (Grassi et al., 2017; Iyer et al., 2015). Integrative modeling frameworks that include land sector, energy sector, transportation, and other interconnected carbon sources and sinks have continued to develop more detailed model structures and higher-resolution data input (Kyle et al., 2011; Wise et al., 2014).

IAMs, designed to answer questions about carbon management, include 1) social and economic factors that drive GHG emissions as well as a representation of biogeochemical cycles that determine the fate of those emissions and 2) the effects on climate and human welfare. The dynamic interactions among sectors in these models mean that they can reveal nonintuitive outcomes. Actions in one sector or geography can influence those in another, and a common goal of carbon management policy is to limit the accumulation of CO_2 in the atmosphere. Therefore, understanding the economy-wide influences of policy choices is critical both to assess the actual consequences of a single policy on carbon accumulation in the atmosphere and to have a realistic idea of the level of atmospheric CO_2 that could be achieved with multiple countries and multiple policies.

Continued efforts to integrate IAMs, ESMs, carbon accounting, and national-scale resource modeling will help develop consistency in data input across these modeling platforms. The combination of global IAMs, national and subnational natural resource economic models, carbon accounting methods, land-use change models, energy technology, and market analyses are all needed to estimate carbon management strategies in a comprehensive manner from the local to global scale (see Box 18.2, Carbon Modeling Needs for Decision Making, p. 744). As one example, a process using IAMs, global and national natural resource (i.e., timber) models, and inventory data (i.e., field surveys) was conducted in the development of the *United States Mid-Century Strategy for Deep Decarbonization* (White House 2016).

18.4.3 Carbon and Greenhouse Gas Accounting

Data and models that estimate changes in carbon flux often were not initially developed for estimating direct and indirect net carbon changes associated with given activities. This is true for country-level inventory data reported by sector (U.S. EPA 2016), biogeochemical cycle models (Del Grosso et al., 2002), and integrated climate models (Wise et al., 2009). In many cases, incorporating the influence of particular activities on upstream or downstream energy, land use, and associated GHG emissions significantly changes estimates of the realized carbon savings. Full GHG accounting of all emissions related to a given activity can significantly augment or reduce reported emissions compared to partial or incomplete accounting.

Accounting of carbon fluxes and stock changes in ecosystems or industrial systems dates back to early work on energy input and output models and systems modeling (Odum 1994) and has evolved rapidly since then. A systems analysis can be developed to understand and quantify net carbon exchange associated with specific management activities (Schlamadinger and Marland 1996). Such analyses, for example, consider disturbance (e.g., widespread tree mortality and erosion from hurricanes or ice storms), forest regrowth over time, landscape area boundary, and forest growth trends over time in the absence of disturbance (Lippke et al., 2011; Lippke et al., 2012). Fossil fuel offsets associated with harvested wood and wood products are also included in these system-scale carbon budgets. These types of analyses often are conducted to illustrate the methods and provide an averaged national answer. To be

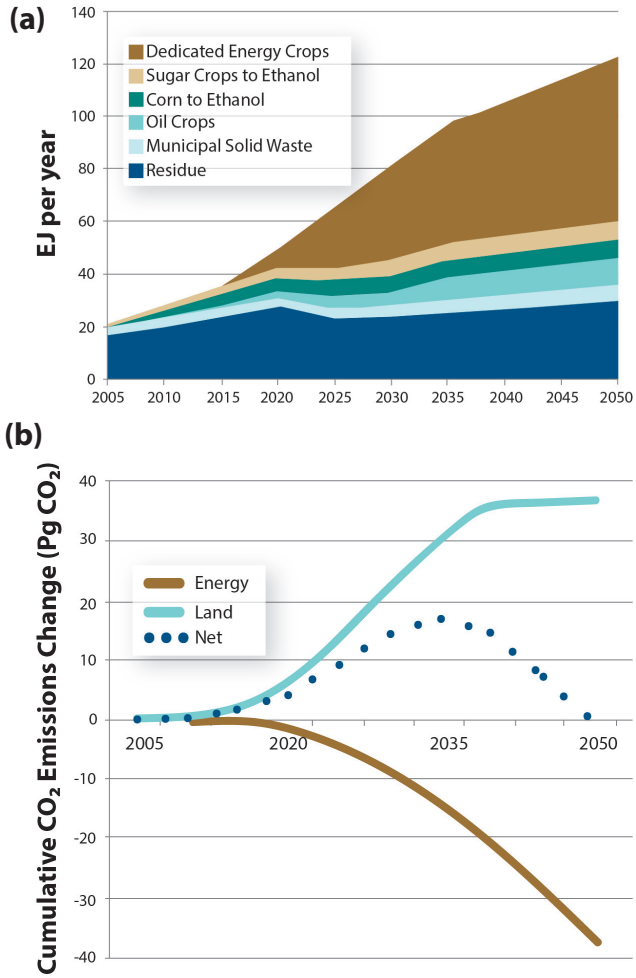

Figure 18.3. Example of Results from a Global Integrated Assessment Model. The illustration considers **(a)** economic market dynamics, land-use change, land resources, and impacts on the carbon cycle that are associated with a high-biofuels mandate scenario. **(b)** Net change in cumulative emissions of carbon dioxide (CO_2) from land-use change and energy systems in high-biofuels scenarios is shown in comparison to the baseline. Key: EJ, exajoules; Pg, petagrams. [Figure source: Redrawn from Wise et al., 2014, copyright Elsevier, used with permission.]

Box 18.2. Carbon Modeling Needs for Decision Making

- Link Integrated Assessment Models, natural resource management models, and socioeconomic models for predictive capabilities such that regional scale analysis can be conducted while being informed and constrained by global economic market dynamics.
- Improve projections for national land-use emissions in the United States and other countries.
- Increase understanding of drivers of land-use change in different global regions.
- Evaluate model predictions through hindcasting, model diagnostics, and multi-model intercomparisons.
- Evaluate how scenario results change depending on the time step used (i.e., subannual to decadal), spatial resolution of model input data, and spatial extent of output.
- Assess and further develop uncertainty quantification methods for carbon-related modeling activities.

Box 18.3. Carbon Accounting Needs for Informing Decision Making

- Elicit user needs for carbon accounting through a two-way dialogue, and socialize the resulting needs and understanding in the carbon cycle science community.
- Conduct regionally specific carbon accounting for dominant activities in land management and fossil fuel management.
- Quantitatively understand how activities affect entire supply chains.
- Perform landscape-scale life cycle analysis that capture regional differences.

useful for decision making, full carbon accounting would need to be conducted for regions that have obvious differences in ecosystem attributes, climate regimes, and social and economic drivers (see Box 18.3, Carbon Accounting Needs for Informing Decision Making, this page).

Past development of carbon accounting methods suggests a number of basic carbon accounting guidelines. Properly defining time and space boundaries of the system or activity of interest is an essential first step, and highlighted below are additional guidelines.

Stock Changes Are Less Prone to Error than Adding up All Biological Fluxes and Uptakes. This finding is currently guiding analyses by EPA's Science Advisory Board Panel on Biogenic Emissions from Stationary Sources on net carbon emissions from the use of biomass for energy production (U.S. EPA 2014). The stock change approach also has been the chosen method for estimating net emissions from forests and agricultural soils (U.S. EPA 2016). Trying to simulate all fluxes in and out of a system is useful for understanding ecosystem processes and climate feedbacks, but the increased complexity may introduce additional error and uncertainty. In contrast, changes in carbon stocks inherently combine the net result of multiple fluxes into and out of a given stock entity. Differences in complex models and stock change methods are exemplified in an analysis by Hayes et al. (2012).

Accounting for Energy and Emissions One-Level Upstream and Downstream Is Often Sufficient to Capture Adequately the Total Flux Associated with an Activity of Interest. When estimating emissions associated with changes in fertilizer application rates, for example, the fuels used to process

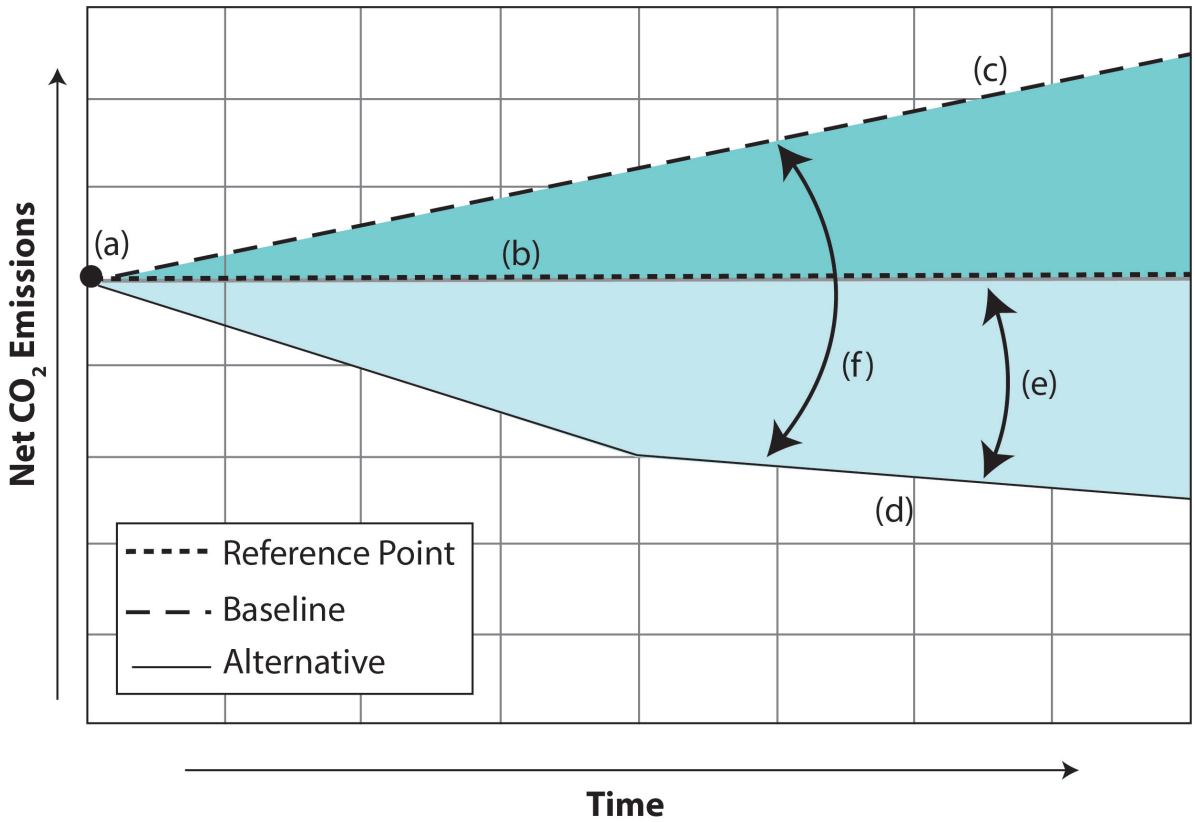

Figure 18.4. Illustration of Basic Hypothetical Carbon Accounting Scenario. Accounting begins at **(a)** the reference point and continues through time with the **(b)** reference line or the **(c)** estimated baseline, and the **(d)** observed or estimated impact of alternative management. Depending on the use of a reference line or baseline, the carbon savings in this hypothetical scenario would be comparatively **(e)** less or **(f)** greater, respectively.

the fertilizer (e.g., natural gas) should be considered (i.e., Level 1 upstream), but the energy used to mine the fuel (e.g., natural gas; Level 2 upstream) is often statistically insignificant (West and Marland 2002). Although exceptions should always be considered, accounting for emissions of both Level 1 upstream and downstream (e.g., transporting the fuel) of the activity of interest remains a good general rule.

Establishing the Proper Reference Point (System that Exists Prior to Changes in Management) Is Essential. The reference point is the current system, prior to a change in activity (see Figure 18.4, this page). The reference point should not be chosen at a time prior to the current activity (e.g., based on historical trends), nor should it be arbitrarily chosen before or after activities associated with the new or alternative management. This issue is currently debated in regard to some forest management techniques (Campbell et al., 2012; Hurteau and North 2009).

A Baseline Trajectory May Be Conceptually More Comprehensive Than a Reference Point But May Have More Uncertainty. Models that project changes in land use, fossil fuel combustion, or other GHG emissions can be particularly useful for understanding future scenarios. However, the trend line for the future trajectory can be uncertain, and using baselines to compare new or alternative systems should only be done with caution (Buchholz et al., 2014). The use of a reference point or baseline should be decided based on the certainty associated with baseline projections (see Figure

18.4). For example, a baseline of forest growth (e.g., increased growth until forest maturation) is well established in forest growth curves, whereas future changes in land use based on commodity markets is less certain. There may also be policy considerations that influence whether baselines or reference points are more appropriate for a given context.

18.4.4 Systems Approach for Decision Making

Combining several of the aforementioned capabilities (e.g., data collection, modeling, and accounting) can help facilitate the use of research products for both decision making and the next generation of new relevant scientific analyses (West et al., 2013). Data assimilation systems have been under development to bring together inventory-based datasets, atmospheric modeling, global land models, and accounting procedures. Integrating these research areas using data assimilation, where appropriate, can help researchers explore data similarities and differences, reconcile data differences, and potentially integrate datasets to attain enhanced data products or model results with reduced bias, reduced uncertainty, and improved agreement with observations. Past efforts include 1) a project in the midwestern United States (Ogle et al., 2006), 2) a North American continental analysis (Hayes et al., 2012; Huntzinger et al., 2012), and 3) similar analyses in Europe (Le Quéré et al., 2015). Of these analyses, those for the midwestern United States and Europe resulted in little to no statistical difference between bottom-up and top-down emissions estimates, indicating promising capability in using one method to constrain another and in integrating methods for a more comprehensive and potentially more accurate estimate. There also is an indication that atmospheric inversion model estimates (i.e., top-down estimates) can be useful in smaller regions, but they are potentially less informative or accurate at continental or global scales (Lauvaux et al., 2012). Accounting issues also were identified and resolved between atmospheric estimates and terrestrial-based estimates so that the two methods could be compared and contrasted, contributing to a new lexicon that helped define land-based fluxes in a manner consistent with fluxes observed from atmospheric measurements (Chapin et al., 2006; Hayes and Turner 2012).

Although reconciling bottom-up and top-down estimates can help build confidence in existing estimates, thereby forming a stronger foundation for decision making, other existing modeling systems could be combined to improve national and global decision making about carbon. Largely independent efforts continue for climate modeling, land-use modeling, global and regional economic modeling, and energy modeling. Coordinating these modeling activities so that, at a minimum, output from one model can be used as input for other models would help in coordinating decisions that inherently affect or are affected by climate, land use, and energy production and consumption (see Figure 18.1, p. 730). This effort would require high-level coordination among research organizations that support modeling in different research fields covering fundamental, applied, and social sciences (see Box 18.4, Research Needs for Integrative Observation and Monitoring Systems, this page).

Box 18.4. Research Needs for Integrative Observation and Monitoring Systems

- Couple life cycle analysis models with Integrated Assessment Models to understand carbon impacts associated with specific activities.
- Use inventory-based land-cover and land-use data in Earth System Models, so that global and regional outputs from carbon-climate models are more useful for decision making.
- Continue research efforts on different methods of observing and modeling carbon sinks and emissions so that existing inventory estimates can be improved and more complete.

18.5 Pathways for Science to Support Decision Making

Carbon cycle science to date has made significant advancements in understanding carbon dynamics and feedbacks between global carbon and climate. For these advances to be more useful in decision making, increased understanding and quantification are needed regarding how individual activities affect carbon sinks and emissions, both directly and indirectly. This information would aid accounting of energy consumption, fossil fuel combustion, as well as land-related emissions and sinks (see Table 18.2, this page). Science-based estimates of net emissions associated with activities, complete with statistical uncertainty, may then be scaled up using relatively high resolution data on environmental conditions and human activities. This information then can be used to better understand how decisions under consideration by public and private entities may impact carbon sources and sinks.

Many land-management decisions at the U.S. Federal and state level (i.e., conservation programs) over the past decade could not have been made without the previous generation of work on carbon cycle science and efforts that supported basic research, fostered co-production of knowledge, and linked scientific inputs with the needs for inventories, assessments, projections, and decision making. Yet, with the evolving interests of communities and policymakers, as well as new policy requirements for implementing and setting national goals, new needs have emerged that emphasize input from the scientific community at the international, national, and subnational levels. Establishing strong partnerships among scientists, stakeholders, and funding sources may be essential for making effective use of carbon-related research over the coming years.

Table 18.2. Research to Support Carbon Cycle Decision Making

Decision-Making Goal	Information Gap	Research Activity Need
Prioritize activities and geographic regions for soil carbon sequestration and net greenhouse gas (GHG) emissions reductions.	Predict changes in soil carbon based on regional changes in land-management practices.	Calibrate existing soil models with field data and develop multivariate meta-analyses of field data.
Consider carbon stock changes in private and public forest management plans.	Understand net carbon stock changes associated with land-management strategies.	Assess forest carbon stocks and net changes in stocks at the regional and landscape levels associated with fire, regrowth, harvesting, thinning, and wildfire management.
Consider carbon stock changes in land-use planning and in legislation and policies that affect national and global land use.	Understand the connections between direct and indirect land-use change and national and global changes in population, diet, affluence, technology, energy, and water use.	Integrate science-based carbon stock and flux estimates, including uncertainty estimates, with global and regional socioeconomic models.
Increase the use of bioenergy, bioproducts, and renewable energy.	Compare net emissions of alternative technologies to existing technologies and capture regional differences, if warranted.	Conduct life cycle analyses (LCAs) for all proposed bioenergy, bioproducts, and renewable technologies and compare these analyses with LCAs for fossil fuel technologies.

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(Continued)

Table 18.2. Research to Support Carbon Cycle Decision Making

Decision-Making Goal	Information Gap	Research Activity Need
Incentivize sustainable bioenergy.	Develop accurate bioenergy emissions accounting at individual facilities.	Calibrate existing forestry models to accurately reflect forest owner planting responses to market signals.
Protect vulnerable high-carbon landscapes.	Identify land areas at high risk of settlement conversion.	Project trends in urban development and land-management choices.
Maximize carbon mitigation on lands at risk of natural disturbance.	Project natural disturbances and their carbon impacts.	Develop region-specific carbon accounting protocols and management guidance.
Optimize national gross domestic production (GDP), its factors, and GHG emissions.	Understand factors of GDP and emissions and how those factors can be used to decrease emissions while positively affecting GDP.	Include GHG emissions in analyses of GDP and national economic growth.
Optimize energy production and consumption for reduced carbon emissions.	Understand fuel mixes, substitutes, combustion efficiencies, energy intensity, and carbon intensity associated with energy production and use.	Develop and integrate models that investigate carbon intensity of fuel use at local to national scales, with feedbacks to other related sectors (e.g., land resources and bioenergy).

SUPPORTING EVIDENCE

KEY FINDING 1

Co-production of knowledge via engagement and collaboration between stakeholder communities and scientific communities can improve the usefulness of scientific results by decision makers (*high confidence*).

Description of evidence base

Understanding what is useful for decision making can help guide development of science more effectively (Lemos and Morehouse 2005; Moser 2009). In many cases, this development requires little extra time or funding and can be as simple as understanding the formatting of information. For example, experimental data on carbon emissions may be generated daily and at a local level, but information on an annual timescale and at the geopolitical level often is needed to inform decisions. In other cases, matching model results with existing decision-making processes will take time and changes to models and processes. Stakeholder engagement has resulted in the use of science results to support decision making for a number of activities, including 1) new modeling capabilities to estimate national forest carbon and attribution of carbon stock changes (Woodall et al., 2015), 2) methods for estimating methane (CH_4) emissions (Turner et al., 2016), and 3) policy-relevant soil management (Paustian et al., 2016). Boundary organizations that bring together a cross-section of disciplines have been successful in promoting fundamental science that is useful to decision makers (Brown et al., 2016). Inherent in the communication and coordination of science and decision makers regarding Key Finding 1 will be the need to revisit, understand, and define the boundaries among science, policy, and management, as well as fundamental science, use-inspired science, and applied science (Moser 2009). Defining these boundaries will help guide and support the co-production of knowledge.

Major uncertainties

The co-production of knowledge is limited by the success and effectiveness of communication, and the certainty of success depends on the process of engagement.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Communicating information and data formatting needs for carbon stock changes, estimates of net emissions associated with specific activities, and projections of carbon stock and net emissions with uncertainty estimates has helped guide field work, observations, and modeling to meet these needs.

Summary sentence or paragraph that integrates the above information

Carbon-related research that is co-produced by scientists and decision makers helps ensure that science results address questions posed by decision makers. The result for Key Finding 1 is robust science that is useful for addressing societal issues. The likelihood of success is high, based on past successes, and the effectiveness is often determined by the level of participation.

KEY FINDING 2

Integrating data on human drivers of the carbon cycle into Earth system and ecosystem models improves representation of carbon-climate feedbacks and increases the usefulness of model output to decision makers (*high confidence*).

Description of evidence base

For Key Finding 2, the impacts of human management activities on carbon stocks have been analyzed and documented for entity-scale greenhouse gas estimation of agricultural activities (Eve et al., 2014). This information is being integrated into models for use by agricultural land managers. For U.S. forests, attribution of human and natural influences (e.g., harvesting, natural disturbance, and forest age) has been successfully disaggregated using field data and models (Woodall et al., 2015) to help inform decision makers. Finally, to better represent human drivers on climate, carbon stocks, and commodity production and consumption at the global scale, human drivers representing land management are being integrated into Earth System Models (ESMs); Drewniak et al., 2013), and the management of land, energy, and fossil fuels is included in Integrated Assessment Models (IAMs; Chaturvedi et al., 2013; Le Page et al., 2016). As human drivers continue to be included in scientific research models, these models will continue to better represent actual local and global dynamics, thereby becoming more useful for decision making.

Major uncertainties

While inclusion of human drivers in estimates of carbon cycle fluxes and stock changes often results in more useful information for decision making, it also can result in a higher number of model parameters, which can increase statistical uncertainty and variability of model results. However, this increased statistical uncertainty does not necessarily reduce the usefulness of findings for decision making, particularly if the uncertainty is a uniform bias or a broader confidence interval surrounding a stable trend.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Continued inclusion of human drivers within ecosystem models and ESMs will better represent the influence of human activities on the carbon cycle, thereby improving the usefulness of results to decision makers.

Summary sentence or paragraph that integrates the above information

Inclusion of human drivers in carbon cycle models increases the accuracy of models and generates model output that is more useful for decision making. For Key Finding 2, statistical uncertainty may increase or decrease based on the change in model complexity.

KEY FINDING 3

Attribution, accounting, and projections of carbon cycle fluxes increase the usefulness of carbon cycle science for decision-making purposes (*very high confidence*).

Description of evidence base

Carbon cycle fluxes by themselves, both observed and estimated, are useful to understand carbon cycle processes but not particularly useful for decision making. Changes in net emissions associated with changes in human activities in the past, present, and future are particularly useful.

Placing emissions in the context of a baseline or business-as-usual scenario, compared to alternative or new management, is necessary. For Key Finding 3, it is the relative change in carbon stocks and emissions associated with activities, along with tracing these activities to their functions in human well-being, that is most needed by decision makers (see Ch. 6: Social Science Perspectives on Carbon, p. 264). This information often is embedded in science-based models, but to be useful it must be aggregated or synthesized using established carbon accounting protocols.

Carbon accounting of direct and indirect impacts of bioenergy production and consumption has been analyzed (Adler et al., 2007) and included in energy and natural resource economic models (Frank et al., 2011; Mu et al., 2015). While carbon accounting in forestry has a long history of development (Schlamadinger and Marland 1996), there remain issues and debate around the effects of wildfire management on net emissions (Campbell et al., 2012; Hurteau and North 2009) and the use of wood products to offset emissions (Lippke et al., 2011; McKinley et al., 2011). Much of the debate surrounds a relatively new finding that conducting carbon accounting and life cycle analysis at the landscape scale is more representative of the net impact of policies and practices on carbon stocks than doing so at a field or plot scale (Galik and Abt 2012; Johnson 2009). Skog et al. (2014) provides a recent summary of practices that are most effective for reducing net emissions. Developing consistency in accounting and projections across the energy and land sector, along with the tools needed to represent upstream, downstream, and landscape-scale impacts, would be useful for decision making.

Major uncertainties

Representation of net carbon fluxes will become more accurate with the inclusion of established carbon accounting methods. This is evident in the science publication record that illustrates convergence of net emissions estimates associated with changes in management.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Estimating net carbon emissions using established and state-of-the-art carbon accounting methods will increase the usefulness of carbon cycle science results for decision makers. Conducting more research in this area, particularly among researchers involved in carbon accounting and basic carbon cycle science, will be essential to generating science-based findings useful for decision making.

Estimated likelihood of impact or consequence, including short description of basis of estimate

Improvements in projection capabilities very likely will help guide decisions associated with energy, land use, and the carbon cycle. Increased use and development of accounting and attribution methods also are highly likely to improve the understanding of changes in carbon stocks and emissions and the application of this understanding to decision making.

Summary sentence or paragraph that integrates the above information

For Key Finding 3, different methods of carbon accounting result in different estimates of carbon stocks and emissions, thereby resulting in inconsistent science results. Use of established carbon accounting methods by researchers in carbon cycle science research will increase consistency in carbon emissions estimates associated with given activities, thereby providing more useful information to decision makers and more useful metrics for comparison within the research community.

KEY FINDING 4

Developing stronger linkages among research disciplines for Earth system processes, carbon management, and carbon prediction, with a focus on consistent and scalable datasets as model inputs, will improve joint representation of natural and managed systems needed for decision making (*high confidence*).

Description of evidence base

Integration and coordination among global climate models, land models, and IAMs are occurring. National land management models and natural resource economic models also are becoming increasingly integrated. However, there remains a gap between global climate and IAMs and national land-use and economic models. The latter are used more often for decision making, but the former are critical in understanding global feedbacks among carbon, climate, economics, and land-use change. For Key Finding 4, increased communication and links between global drivers and subnational dynamics that impact carbon (Beach et al., 2015; de Vries et al., 2013; Kraucunas et al., 2014; Verburg et al., 2009) could help develop comprehensive science-based systems to better inform decision making. Efforts like this will depend on cross-sectoral and cross-scale research to better understand how to integrate or link needed components and scales.

Major uncertainties

Uncertainties exist in successful development of models across scales (e.g., local, regional, continental, and global).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

A more complete picture of carbon dynamics across scales, using more realistic representation of actual stocks and emissions, will increase the accuracy of carbon models and their use by decision makers.

Estimated likelihood of impact or consequence, including short description of basis of estimate

The likelihood of impacts is high, although developing links between national- and global-scale data and models can be challenging, and success is less certain.

Summary sentence or paragraph that integrates the above information

For Key Finding 4, connections between global biogeochemistry and climate models with subnational land management models will be useful to understand the feedbacks between global carbon cycles and carbon management activities. Linking models or model output and input is often challenging and includes a level of inherent uncertainty.

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19 Future of the North American Carbon Cycle

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KEY FINDINGS

1. Emissions from fossil fuel combustion in the North American energy sector are a source of carbon to the atmosphere. Projections suggest that by 2040, total North American fossil fuel emissions will range from 1,504 to 1,777 teragrams of carbon (Tg C) per year, with most coming from the United States (~80%, or 1,259 to 1,445 Tg C per year). Compared to 2015 levels, these projections represent either a 12.8% decrease or a 3% increase in absolute emissions (*high confidence*).

2. Land, ocean, coastal, and freshwater systems are currently net sinks of carbon from the atmosphere, taking up more carbon annually than they release. However, emerging understanding suggests that the future carbon uptake capacity of these systems may decline, depending on different emissions scenarios, with some reservoirs switching from a net sink to a net source of carbon to the atmosphere (*high confidence*).

3. Human-driven changes in land cover and land use will continue to be key contributors to carbon cycle changes into the future, both globally and in North America. Globally, land-use change is projected to contribute 10 to 100 petagrams of carbon (Pg C) to the atmosphere by 2050 and between 19 and 205 Pg C by 2100. Conversely, in the United States, land use and land-use change activities are projected to increase carbon stocks in terrestrial ecosystems by about 4 Pg C from 2015 to 2030. This projected increase is primarily driven by the growth of existing forests and management activities that promote ecosystem carbon uptake, often in response to changes in market, policy, and climate (*high confidence*).

4. The enhanced carbon uptake capacity of ocean and terrestrial systems in response to rising atmospheric carbon dioxide (CO_2) will likely diminish in the future. In the ocean, warmer and more CO_2-enriched waters are expected to take up less additional CO_2. On land, forest maturation, nutrient limitations, and decreased carbon residence time in soils will likely constrain terrestrial ecosystem response to rising CO_2 (*high confidence*).

5. Soil carbon losses in a warming climate will be a key determinant of the future North American carbon cycle. An important region of change will be the Arctic, where thawing permafrost and the release of previously frozen carbon will likely shift this region from a net sink to a net source of carbon to the atmosphere by the end of the century (*very high confidence*).

6. Carbon storage in both terrestrial and aquatic systems is vulnerable to natural and human-driven disturbances. This vulnerability is likely to increase as disturbance regimes shift and disturbance severity increases with changing climatic conditions (*high confidence*).

Note: Confidence levels are provided as appropriate for quantitative, but not qualitative, Key Findings and statements.

19.1 Introduction

The physical climate system and the carbon cycle are tightly coupled. Each is sensitive to changes in the other, leading to complex feedbacks between the two (Ciais et al., 2013). A core goal of carbon cycle research is to understand how the carbon cycle will interact with and influence future climate (Michalak et al., 2011). In addition to changing climate (e.g., changing temperature and precipitation patterns), the carbon cycle is sensitive to changing atmospheric composition (e.g., ozone and nutrient deposition), extreme events such as droughts and floods, disturbances including fire and insects, and human activities such as fossil fuel emissions and land-management decisions. Land, ocean, coastal, and freshwater systems currently are net "sinks" of carbon from the atmosphere (e.g., Le Quéré et al., 2016), meaning that they annually take up more atmospheric carbon than they release, but emerging understanding of these systems (e.g., Raupach et al., 2014) suggests the possibility of a decline in their future carbon uptake capacity. Furthermore,

some reservoirs could switch from a net sink to a net "source" of carbon to the atmosphere (e.g., Canadell et al., 2010; Schimel et al., 2015). Projecting future carbon cycle changes thus requires the ability to estimate the response of land and aquatic systems to numerous, often competing, drivers. Equally important to identifying the vulnerability of specific carbon reservoirs is understanding the processes controlling their behavior to better inform management and policy decisions (Canadell et al., 2010).

This chapter reviews current understanding of potential changes in the carbon budget of major global and North American carbon reservoirs. Also examined are the drivers of future carbon cycle changes including carbon-climate feedbacks, atmospheric composition, nutrient availability, human activity, and resource management decisions. Not all carbon reservoirs are equally vulnerable or resilient to changing climate, nor will they have the same response to these drivers. The majority of work examining future carbon cycle changes and potential feedbacks with climate has been conducted at the global scale as part of coupled carbon-climate model intercomparison efforts, including the Coupled Model Intercomparison Project Phase 5 (CMIP5; Friedlingstein 2015; Friedlingstein et al., 2014). These global projections are summarized in Sections 19.3–19.6, p. 763. However, projections of future carbon cycle changes specific to North America remain limited. Where possible, this chapter includes projected changes in net carbon uptake and release by the North American land surface out to 2100 (see Section 19.4, p. 771). Also examined are the likely drivers of future changes in the North American carbon cycle as they relate to terrestrial, ocean and coastal, and freshwater systems (see Sections 19.4–19.6). Finally, this chapter highlights ongoing knowledge gaps and research needs critical for improving understanding of future carbon cycle changes (see Section 19.7, p. 780).

Such a discussion of future carbon cycle changes is new in the *Second State of the Carbon Cycle Report* (SOCCR2). Since the *First State of the Carbon Cycle Report* (SOCCR1; CCSP 2007), progress has been made at identifying the vulnerability of key carbon pools, including high-latitude permafrost (see Ch. 11: Arctic and Boreal Carbon, p. 428), soils and peatlands (see Ch. 12: Soils, p. 469), temperate forests (see Ch. 9: Forests, p. 365), and freshwater wetlands (see Ch. 13: Terrestrial Wetlands, p. 507). Other progress includes greater understanding of potential carbon losses in terrestrial ecosystems subject to disturbance events, such as insects, fire, and drought (see Ch. 9: Forests), as well as the impact of increasing atmospheric carbon dioxide (CO_2) on terrestrial and aquatic systems (see Ch. 17: Biogeochemical Effects of Rising Atmospheric Carbon Dioxide, p. 690). Synthesizing and building on this previous information, this chapter focuses on potential future changes to the North American carbon cycle while putting it in a global context. Finally, this chapter covers multiple carbon stocks and flows, each with different standard conventions in terms of units and metrics. Any change in unit from mass of carbon (e.g., teragrams of carbon [Tg C] or petagrams of carbon [Pg C]) to mass of CO_2 or methane (CH_4) or CO_2 equivalent (CO_2e) has been clearly marked.

19.2 Overview of the Global Carbon Cycle

In Earth's past and over geological time, the global carbon cycle and Earth's climate have changed as a result of external factors and complex interactions within the Earth system (see Ch. 1: Overview of the Global Carbon Cycle, p. 42, for more details). In addition, carbon cycle feedbacks with the climate system can both amplify and dampen the effects of these external forcings (Graven 2016).

The global carbon cycle can be viewed as a system of reservoirs (e.g., atmosphere, ocean, and land). A reservoir's size (or pool) depends on the balance of carbon flowing into and out of it (i.e., the net flux; see Ch. 1: Overview of the Global Carbon Cycle, p. 42). Because Earth's carbon cycle is a closed system in which outputs from one reservoir are inputs to another, knowing how and why the amount of carbon stored in a reservoir is changing requires understanding the different processes affecting the reservoir's carbon inputs and outputs. In addition, the processes that affect the size of carbon flows

(fluxes) are often influenced by the amount of carbon stored in the reservoir (i.e., the reservoir's size). For the amount of carbon stored in these vast reservoirs to shift noticeably, a net change in the balance of inputs and outputs (i.e., the net flux) must be either large or sustained long enough for the change to accumulate.

The amount of atmospheric CO_2 depends on the balance between CO_2 emissions to the atmosphere and carbon uptake by the land and ocean (see Ch. 8: Observations of Atmospheric Carbon Dioxide and Methane, p. 337). Since the dawn of the Industrial Revolution around 1750, fossil fuel extraction and burning have transferred a net 375 ± 30 Pg C from geological reservoirs to the atmosphere (Ciais et al., 2013). In addition, increasing conversion of forests to agricultural land, growing demand for wood, and other factors of land-use change have transferred carbon from vegetation and soil reservoirs to the atmosphere. Only about half of the CO_2 emitted from fossil fuel burning, industry (e.g., cement manufacturing), and land-use change has accumulated in the atmosphere. The rest has been taken up by the land and the ocean. The current strength of land and ocean carbon uptake from the atmosphere is the result of complex interactions among many factors (Ciais et al., 2013). Details about these processes and their current budget, at both global and North American scales, are provided in detail in Ch. 1: Overview of the Global Carbon Cycle and Ch. 2: The North American Carbon Budget, p. 71.

19.3 Major Drivers of Carbon Cycle Changes and Their Future Projections

During the coming decades and centuries, human-driven CO_2 emissions are expected to continue to drive changes in climate (Gregory et al., 2009) and thus the carbon cycle. Model projections of how the future may evolve with respect to climate change and the carbon cycle are commonly driven by a set of plausible future scenarios. These scenarios are useful in helping to inform decision making by offering insights into possible tradeoffs related to different types of actions or policies. While these scenarios often are not an exhaustive treatment of all mitigation or energy resource options, they do consider plausible changes to market structures and energy production capacity, as well as technological advancements and existing and potential policies to reduce CO_2 and other greenhouse gas (GHG) emissions (e.g., EIA 2016; Mohr et al., 2015; van Vuuren et al., 2011).

At the global scale, a series of Representative Concentration Pathways (RCPs) was created for CMIP5 using different integrated assessment models. These RCPs consider alternate socioeconomic pathways that result in different emissions levels for both fossil fuel use and land-use change, and thus different potential atmospheric GHG concentrations (Jones et al., 2013; van Vuuren et al., 2011). These RCPs are used to drive Earth System Models (e.g., CMIP5; Friedlingstein 2015; Friedlingstein et al., 2014) in order to project potential climate and carbon cycle changes at global and regional scales. The set of four pathways used by CMIP5 and similar studies are representative of the range of scenarios presented in the literature and include one mitigation scenario leading to very low radiative forcing (RCP2.6), two medium stabilization scenarios (RCP4.5 and RCP6.0), and one high baseline emissions scenario (RCP8.5; van Vuuren et al., 2011). Each RCP is named after its target radiative forcing, measured in watts per square meter (W/m^2), in the year 2100. A general description of the RCPs is provided next and in Figure 19.1, p. 764, and Figure 19.2, p. 765. More details on the characteristics of each RCP are available in van Vuuren et al. (2011).

1. **RCP8.5 High Emissions Scenario.** Projects increasing CO_2 and CH_4 emissions over time due to increased energy intensity as a result of high population growth and lower rates of technology development leading to radiative forcing of 8.5 W/m^2 by 2100. This scenario assumes an increase in cropland and grassland area driven by the demands of population growth.

2. **RCP6.0 Stabilization Scenario.** Projects a range of technologies and strategies to reduce

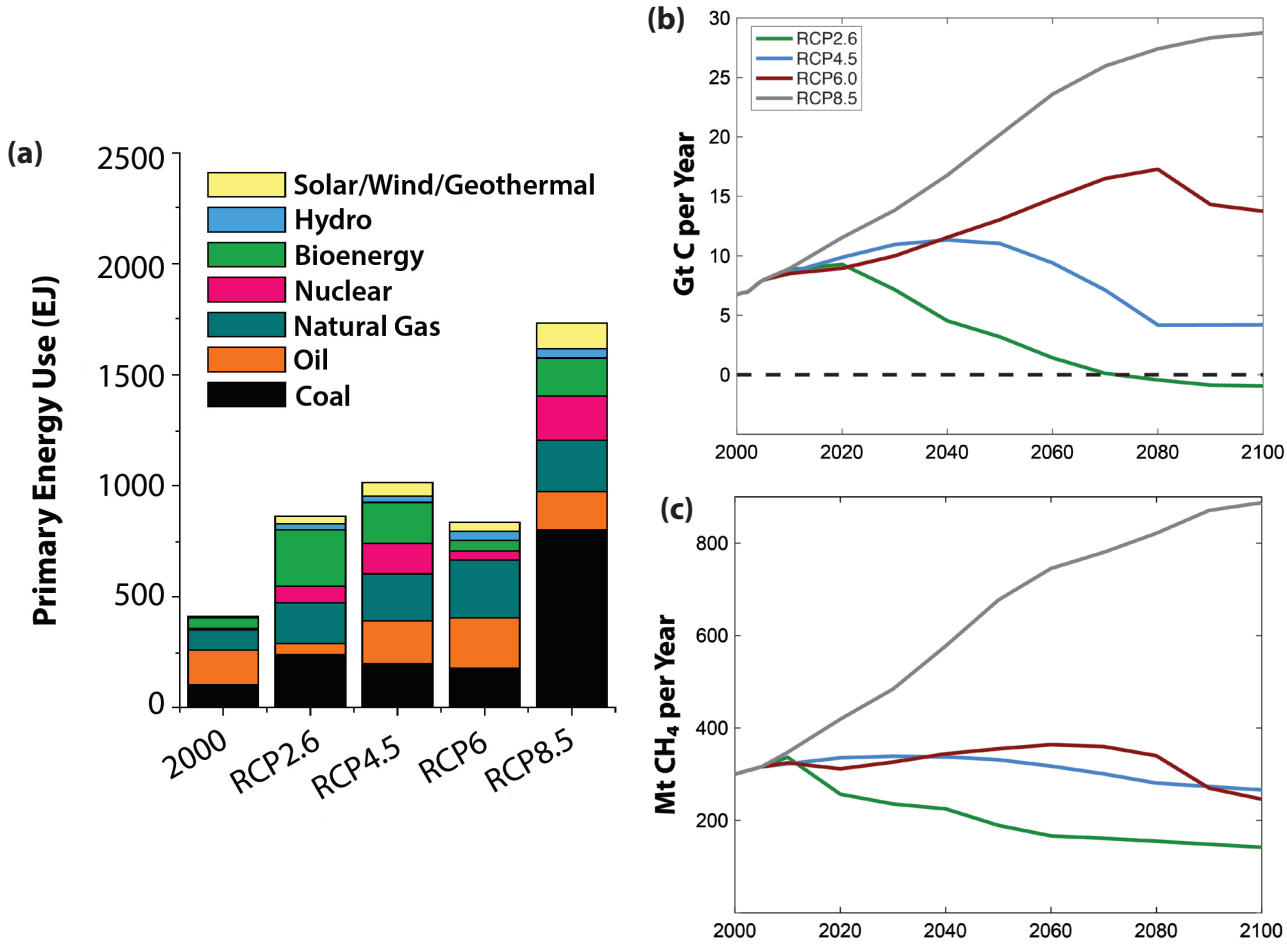

Figure 19.1. Projected Global Energy Consumption and Emissions. Projections of **(a)** primary energy consumption in exajoules (EJ) by source and emissions of **(b)** carbon dioxide measured in gigatons of carbon (Gt C) and **(c)** methane (CH_4) measured in megatons (Mt) under the four different Representative Concentration Pathways (RCPs). [Figure source: Adapted from van Vuuren et al., 2011, used with permission under a Creative Commons Attribution Noncommercial License.]

CO_2 emissions after the year 2080, coupled with fairly steady CH_4 emissions throughout the century to stabilize radiative forcing at 6 W/m^2 in 2100. This scenario assumes an increase in cropland area, but a decline in pasture area due to aggressive implementation of intensive animal husbandry.

3. **RCP4.5 Stabilization Scenario.** Projects a range of technologies and strategies to reduce CO_2 emissions after 2040, coupled with fairly steady CH_4 emissions throughout the century to stabilize radiative forcing at 4.5 W/m^2 in 2100. This scenario assumes a decrease in cropland and grassland area due to climate policies that value carbon in natural vegetation.

4. **RCP2.6 Low Emissions Scenario.** Projects an increased use of bioenergy and carbon capture and storage, which leads to a substantial reduction in CO_2 emissions after 2020. This reduction coupled with declining CH_4 emissions from energy production, transportation, and livestock leads to a peak in radiative forcing of

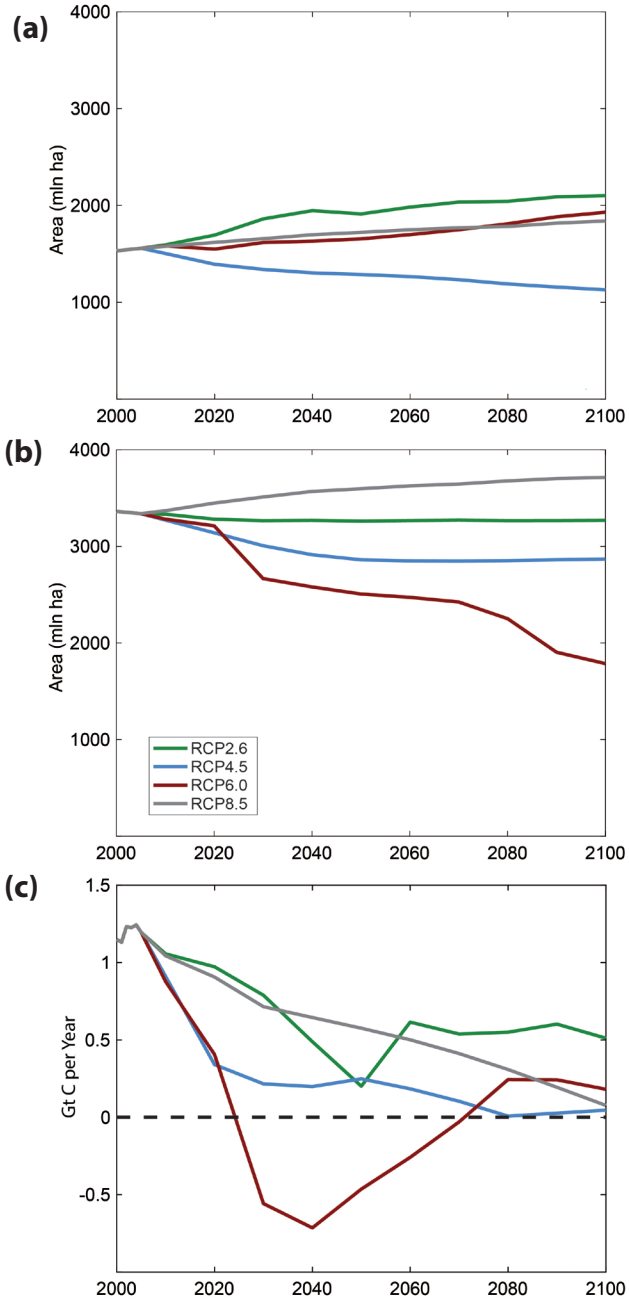

Figure 19.2. Projections of Future Land-Use Area and Land-Use Emissions. Projections of land-use area in hectares (ha) for **(a)** croplands and **(b)** grasslands, along with **(c)** carbon dioxide emissions related to land use measured in gigatons of carbon (Gt C) under the four Representative Concentration Pathways (RCPs). [Figure and data sources: Panels (a) and (b) are adapted from van Vuuren et al., 2011, used with permission under a Creative Commons Attribution Noncommercial License. Panel (c) is derived from data in Meinshausen et al., 2011.]

3 W/m^2, followed by a decline to 2.6 W/m^2 by 2100. Cropland area increases, but largely as a result of bioenergy production. Grassland area remains relatively constant as the increase in animal production is offset by more intensive animal husbandry.

These RCPs describe a range of plausible global emissions and land-use scenarios that will drive changes in global climate. Later in this chapter, CMIP5 projections driven by these scenarios will be used to discuss projected changes in the North American land and coastal ocean carbon cycles. Section 19.3.1, this page, summarizes projected trends of human-driven emissions from fossil fuel use, and Section 19.3.2, p. 766, summarizes land-use management and change specific to North America. Also described is how climate is projected to change in North America according to different projections of future global emissions (see Section 19.3.3, p. 770). Even though the following sections primarily focus on changes over North America, these changes have been placed in a global context as necessary.

19.3.1 Fossil Fuel Emissions

Fossil fuels are vital to current North American energy needs, accounting for about 80% of global energy consumption (Mohr et al., 2015). Emissions from fossil fuel combustion in North America's energy sector currently represent a source of carbon (mostly as CO_2) to the atmosphere and will continue to be a source into the future. Projections suggest that by 2040, total North American fossil fuel emissions will range from 1,504 to 1,777 Tg C per year (see Table 19.1, p. 766). Compared to 2015, this range represents either a 12.8% decrease or a 3% increase in absolute emissions. These estimates are based on a range of projections for each country and provide "high" and "low" bounds for potential future North American carbon emissions from fossil fuel burning.

Energy market projections, and subsequently fossil fuel emissions futures, are subject to large uncertainties because many of the factors that shape energy decisions and future developments in technologies,

Table 19.1. Projected Energy-Related Emissions from Fossil Fuel Burning for Canada, Mexico, the United States, and North America from 2015 to 2040

Canada (Teragrams of Carbon [Tg C])	2015	2020	2030	2040
High (High Emissions Scenario, Rapid Growth)	174	181	193	193
Low (Low Emissions Scenario, Slow Growth)	174	176	168	168
Source: ECCC 2016a; values for 2040 assumed to be similar to 2030.				
Mexico (Tg C)				
High (Current Policies)	118	117	127	140
Low (New Policies)	118	111	97	78
Source: Mexico Energy Outlook (IEA 2016).				
United States (Tg C)				
High (Reference Case Without Clean Power Plan)	1,434	1,442	1,421	1,445
Low (Low Economic Growth)	1,434	1,419	1,284	1,259
Source: U.S. Department of Energy Annual Energy Outlook (EIA 2017).				
North America (Tg C)				
High	1,726	1,740	1,740	1,777
Low	1,726	1,705	1,549	1,504

Values are based on those reported in Ch. 3: Energy Systems, p. 110, and represent a synthesis of projections from three sources: U.S. Department of Energy's Energy Information Administration (EIA 2017), Environment and Climate Change Canada (ECCC 2016a), and Organisation for Economic Cooperation and Development's International Energy Agency (IEA 2016).

demographics, and resources cannot be robustly foreseen. These factors include economic and population growth, energy prices, technology innovation and adoption, policies, laws, and regulations. Fossil fuel emissions also can be altered through global organization and cooperation.

Future reductions in emissions often are pursued against a continuing upward trend of population growth and energy use. As such, a timeline to reach peak emissions and reverse emission trends is a goal embraced by several countries. These commitments require complex and comprehensive analyses that project energy sources, production, consumption, and efficiency practices across sectors. Creating baseline and alternative scenarios and assessing their accuracy are areas of continued research (see Ch. 3: Energy Systems, p. 110, for more details on energy and fossil fuel emission trends within North America and their future outlook).

19.3.2 Land-Use Management and Land-Cover Change

Often the terms "land cover" and "land use" are used synonymously, albeit incorrectly. Land cover indicates the Earth's observed physical and biological land cover, whereas land use encompasses how people use land for shelter, food, feed, fiber, and fuel production, including activities such as livestock grazing, deforestation, and urbanization (IPCC 2000). All these land-use activities influence the exchange of carbon, heat, and water between the land and atmosphere (Pielke et al., 2016; USGCRP 2017a). People's use of land shifts in response to evolving policies, land-use investments, and market preferences and demands. Land use is also affected

by environmental and socioeconomic conditions including population and economic growth. The land-use decisions emerging from these changing conditions affect ecosystem functioning and the land carbon cycle. As a result, land use and land-cover change will play a large role in determining how the future carbon cycle, and thus global climate, will function and change (Barker et al., 2007; Brovkin et al., 2006; Gitz and Ciais 2004). Highlighted next are some recent trends in emissions from land use and land-cover change to provide context for projected future changes. See Ch. 2: The North American Carbon Budget, p. 71, for a more detailed discussion on emissions from current land use and land-cover change.

In 2014, land use and land-use change involving forests in Canada and Mexico resulted in net annual emissions of 72 Tg CO_2e[1] (ECCC 2016a). Most of these emissions resulted from forest fire and insect disturbance (Canada). In the United States and Mexico, however, land use, land-use change, and forestry (LULUCF) activities resulted in overall net carbon sequestration of 763 Tg CO_2e (U.S. EPA 2016) in 2014 and 142 Tg CO_2e in 2013 (SEMARNAT-INECC 2016), respectively. The most prominent changes in U.S. land use and land cover in recent decades involve the amount and type of forest cover (Brown et al., 2014) affected through logging and development in the Southeast and Northwest, as well as urban expansion in the Northeast and Southwest. Although total carbon sequestration by LULUCF has increased about 4.5% from 1990 to 2014 (U.S. EPA 2016), this trend—which largely depends on forest area, health, and product markets—is not guaranteed to persist into the future. Some studies estimate a significant decrease in the rate of future carbon uptake by forests resulting from changes in both forest age and land use as a result of increasing population and subsequent demand for agricultural commodities (see Ch. 9: Forests, p. 365). However, other studies suggest U.S. forests will remain a large carbon sink because of investments in the forest sector (Tian et al., 2018) and CO_2 fertilization (e.g., Tian et al., 2016) that will bolster future forest carbon stocks. The range of potential future changes in these stocks is captured in the diverging (e.g., increasing and decreasing) confidence bands associated with projected forest carbon stocks after 2020 in U.S. land-use projections (U.S. Department of State 2016). Nevertheless, future changes in forest carbon stocks will vary geographically and depend on environmental conditions including water availability (Beach et al., 2015; U.S. EPA 2015).

Agricultural emissions, including non-CO_2 gases like CH_4 (see Box 19.1, Future Methane Cycle, p. 768) and nitrous oxide (N_2O), associated with cropland and livestock management also play an important role in overall emissions levels (see Ch. 5: Agriculture, p. 229). U.S. agricultural production resulted in GHG emissions totaling 516 Tg CO_2e in 2013. These emissions are projected to decline slightly to 494 Tg CO_2e by 2030 (U.S. Department of State 2016). Although total cropland area has remained fairly stable over the past 30 years (USDA 2017), cropland could slowly expand with population increases and economic growth. Furthermore, urban land cover could increase by 73% to 98% by 2050 in the lower 48 states (Bierwagen et al., 2010; Wear 2011). Future increases in cropland and urban areas may result in grassland and forest area losses, but the extent of increased cropland area will depend largely on environmental policies, changes in international trade of agricultural commodities, and advancements in agricultural technologies. Also, crop yield improvements consistent with historical trends could deliver an approximately 50% increase in global primary crop production by 2050 (Ray et al., 2013). More intense cropland management could decrease the need for croplands and, in turn, reduce forest and grassland losses.

Projecting the influence of land use and land-use change on future land carbon cycle dynamics is

[1] Carbon dioxide equivalent (CO_2e): Amount of CO_2 that would produce the same effect on the radiative balance of Earth's climate system as another greenhouse gas, such as methane (CH_4) or nitrous oxide (N_2O), on a 100-year timescale. For comparison to units of carbon, each kg CO_2e is equivalent to 0.273 kg C (0.273 = 1/3.67). See Box P.2, p. 12, in the Preface for more details.

Box 19.1 Future Methane Cycle

Methane (CH_4) is a potent greenhouse gas and precursor for tropospheric ozone formation. Quantifying CH_4 emissions is critical for projecting future climate and air quality changes and essential for developing strategies to mitigate emissions. CH_4 is emitted into the atmosphere from a variety of biogenic, thermogenic, and pyrogenic sources and is removed from the atmosphere predominately by reaction with hydroxyl radicals (OH). Measurement of air trapped in glacial ice suggests that the preindustrial abundance of atmospheric CH_4 was about 720 parts per billion (ppb; Ciais et al., 2013). The contemporary atmospheric CH_4 abundance is about 1,800 ppb, a 2.5-fold increase since preindustrial times. Most of the CH_4 increase in the last century is believed to be a result of increased emissions from human-driven activities, including rice cultivation, ruminant livestock (enteric fermentation and waste management), landfills, and fossil fuel extraction and use. The rate of increase in atmospheric CH_4 concentration decreased in the mid-1980s, approached a near-zero growth rate from 2000 to 2006, and in 2007 resumed an abrupt increase (Dlugokencky et al., 2009; Kai et al., 2011; Rigby et al., 2008). The recent changes in CH_4 concentration growth rates have received much attention (Nisbet et al., 2014; Saunois et al., 2016), although the ultimate cause of these changes remains uncertain and highly debated within the scientific community.

Among anthropogenic sources, the United States reports sectoral projections through its National Communications every 4 years, and every 2 years through its Biennial Reports issued by the Department of State to the United Nations Framework Convention on Climate Change (NASEM 2018). Accurate projections of anthropogenic CH_4 emissions are a key foundation for planning national policies or goals, but these projections are dependent on many factors that are difficult to predict, including future energy and agricultural policies, CH_4 mitigation policies, natural resource development, and population migration. The most recent national projections are presented in the *Second Biennial Report of the United States of America* (U.S. Department of State 2016), which includes projections of total U.S. CH_4 in 2020 (26.8 teragrams [Tg] of CH_4), 2025 (26.96 Tg CH_4), and 2030 (27.28 Tg CH_4), as well as emissions by major source category. The 2025 and 2030 values are about 1% to 2% lower than 2015 emissions values.

Among natural sources, wetland emissions represent the largest and most uncertain natural source of CH_4 emissions, with current estimates ranging from 127 to 227 Tg CH_4 per year (Saunois et al., 2016). An important aspect of the atmospheric CH_4 budget is the sensitivity of natural wetland emissions to climate change (e.g., future soil temperature and moisture) and to atmospheric CO_2 concentrations. Higher soil temperature can lead to increased microbial activity and CH_4 production but also increased soil consumption of CH_4. Increased drought and drying of wetland soils likewise can lead to reduced emissions. Melton et al. (2013) analyzed the response of wetland models to projected changes in air temperature, precipitation, and atmospheric CO_2 abundance over the next century. They found that many models show increased emissions in response to higher levels of CO_2 (via substrate availability) and temperature. However, models with prognostic wetland dynamics project that wetland extent will be reduced in the future, potentially leading to smaller emissions, especially at low latitudes. Using climate scenarios from the *Intergovernmental Panel on Climate Change Fifth Assessment Report*, Stocker et al. (2013) found that wetland CH_4 emissions may increase from

Continued on next page

(Continued)

228 to 245 Tg CH_4 per year in Representative Concentration Pathway (RCP) 2.6 and from 303 to 343 Tg CH_4 per year in RCP8.5. Overall, the future response of wetland emissions to climate change remains highly uncertain but is likely to be a positive feedback in terms of radiative forcing effects (Arneth et al., 2010).

Emissions from the Arctic, in particular, have the potential to increase significantly as temperatures rise and the vast stores of soil carbon thaw (Harden et al., 2012; Schuur and Abbott 2011). The mass of carbon frozen in Arctic permafrost down to 20 m is estimated to be about 1,700 petagrams of carbon (Pg C; Tarnocai et al., 2009), roughly double the approximately 830 Pg C currently in the atmosphere and more than three times what already has been emitted to the atmosphere from fossil fuel use since preindustrial times. As the Arctic warms and permafrost thaws, this ancient carbon may be mobilized to the atmosphere, and a small fraction (about 3%) may be emitted as CH_4 (Schuur and Abbott 2011). Current understanding suggests that approximately146 to 160 Pg C could be released over the next century, primarily as CO_2 (see Key Findings in Ch. 11: Arctic and Boreal Carbon, p. 428). Release of carbon from permafrost is likely to be gradual and occur on century timescales (Schuur et al., 2015). Annually, if this amount of carbon were released at a constant rate, emissions would be far lower than annual fossil fuel emissions (about 9 Pg C per year) but comparable to land-use change (0.9 Pg C per year). Schaefer et al. (2011) pointed out that potential carbon emissions from the Arctic could have important implications for policies aimed at reducing or stabilizing emissions, clearly highlighting the importance of maintaining long-term measurements of atmospheric CH_4 in the Arctic.

Considerable CH_4 is also stored in the ocean as clathrates that may be susceptible to release into the ocean and subsequently into the atmosphere. While there is no conclusive proof that hydrate-derived CH_4 is reaching the atmosphere now, more observational data and improved numerical models will better characterize the climate-hydrate synergy in the future (Ruppel and Kessler 2017).

challenging because of uncertainties in projecting market interactions, potential extent of land-use change, and the associated effect of these changes on terrestrial ecosystems (U.S. Department of State 2016). This uncertainty is reflected in the range of future estimates. Globally, land-use change contributed 180 ± 80 Pg C to the atmosphere from 1750 to 2011 (Ciais et al., 2013). Depending on different scenarios in response to increasing population and management and policy choices, land use and land-cover change are projected to contribute an additional 10 to 100 Pg C to the atmosphere by 2050 and 19 to 205 Pg C by 2100 (Brovkin et al., 2013). These projections account for both carbon loss from vegetation clearing (e.g., for agricultural use, bioenergy crops, and wood products) and carbon gain from vegetation regrowth. Canada's official 2016 emissions projections to 2030 do not include LULUCF emissions or sequestrations. However, according to Canada's Midcentury Strategy, "analyses show that a substantial reduction in emissions and increase in removals by 2050 is possible through measures such as changes in how we manage forests, greater domestic use of long-lived wood products, greater use of bioenergy from waste wood, and afforestation" (ECCC 2016b). Within the conterminous United States, land use, land management, and climate change are projected, on average, to increase carbon stocks by 17 Pg C (368 Tg C per year) from 2005 to 2050 under different future emissions scenarios (Tan et al., 2015). Other estimates, however, indicate less carbon sequestration (3.7 Pg C from

2015 to 2030, or 246 Tg C per year) and higher uncertainty after 2030 (U.S. Department of State 2016). The primary drivers of carbon uptake arising from land-use and land-cover change activities within the United States are growth of existing forests and activities focused on increased carbon uptake such as forest management and tree planting (U.S. Department of State 2016). Uncertainties in future projections of land use, land-use change, and associated impacts on the North American carbon cycle largely stem from uncertainty in population growth and its effects on forest and agricultural land area, particularly after 2030.

Globally, through carbon sequestration and avoided emissions, effective land-based carbon mitigation strategies could prevent up to 38 Pg C from entering the atmosphere by 2050 (Canadell and Schulze 2014). Land-based emission mitigation strategies include avoided deforestation or conversion, afforestation or reforestation, improved land management and livestock practices, new harvested wood product technologies, and bioenergy (Canadell and Raupach 2008; Luyssaert et al., 2014; Van Winkle et al., 2017). However, additional future land-use goals (e.g., food, fiber, and feed production; wildlife management; and other ecosystem services) must be reconciled with strategies for increasing land carbon uptake.

19.3.3 Climate

Since the *Third National Climate Assessment* (Melillo et al., 2014), new observations and research have increased understanding of past, current, and projected changes in climate, both globally and within North America. The current state of knowledge in climate trends and projections for the United States is summarized in the *Climate Science Special Report* (CSSR; USGCRP 2017a). This section summarizes some of these key findings. For more detailed information about the observational evidence and mechanistic explanations for past and projected climate changes, see the full CSSR (USGCRP 2017a).

Global average annual temperatures over both land and ocean have increased by 1.8°F from 1901 to 2016. Similar warming has been observed over the conterminous United States, with the greatest temperature increase (more than 1.5°F in the past 30 years) seen in Alaska, the Northwest, Southwest, and northern Great Plains (USGCRP 2017a). For example, over the past 50 years, the average annual temperature across Alaska has increased at a rate more than twice as fast as the global average. Multiple lines of evidence point to human-driven activity as the dominant cause of the observed warming (USGCRP 2017a). Average annual temperatures across the United States are projected to continue to rise throughout this century, with near-term increases of at least 2.5°F over the coming decades. Much larger increases in temperature (5.8°F to 11.9°F) are projected in the United States by late century under higher human-driven emissions scenarios (USGCRP 2017a).

As the global climate warms, high-latitude regions (e.g., Alaska and Canada) are projected to become wetter, while the subtropical zone (e.g., southern United States) is projected to become drier. In addition, the tropical belt may widen while the subtropical region may shift poleward (Seidel et al., 2008). Within the United States, projected changes in seasonal average precipitation vary and depend on location and season (USGCRP 2017a). Northern parts of the country are expected to become wetter in the winter and spring as global temperatures increase. In the near term, this precipitation increase is likely to fall as snow. However, as average annual temperature continues to rise and conditions become too warm for snow production, wintertime precipitation will mostly fall as rain (USGCRP 2017a). Conversely, the southwestern United States is projected to become drier with less winter and springtime precipitation (USGCRP 2017b). In many regions of the country, however, changes in future average seasonal precipitation are smaller than or consistent with natural historical variations (USGCRP 2017a).

Along with changes in average annual temperature and seasonal precipitation, the frequency and intensity of extreme heat and heavy precipitation events are likely to increase (USGCRP 2017a). For

example, under "business-as-usual" human-driven emissions scenarios (e.g., RCP8.5), the number of heavy precipitation events is projected to be two to three times greater than the historical average in every region of the United States by the end of the century (USGCRP 2017a). Additionally, the number of extremely warm days is projected to increase significantly, along with an increase in heatwave intensity.

Combined, these changes in annual mean temperature and seasonal precipitation, as well as the frequency and intensity of extreme events, can drive changes in the water cycle and, by extension, water quality and availability. Expected water cycle changes also are likely to lead to more intense and prolonged droughts within the United States, particularly in the Southwest. The increasing occurrence and severity of droughts can affect plant and agricultural productivity, carbon uptake, and the likelihood of disturbance events such as fire.

Projected climate change in North America is expected to affect carbon cycling in both land and ocean ecosystems. On land, the processes of photosynthesis, respiration, and decomposition strongly depend on temperature and moisture availability, and changes in either can alter the balance of carbon uptake and release across ecosystems (Jung et al., 2017; Luo 2007; Zscheischler et al., 2014). Similarly, because of the temperature sensitivity of gas solubility in water, warmer temperatures caused by climate change also affect the rate and extent to which atmospheric CO_2 is exchanged with ocean and freshwater systems. Although most physical and biogeochemical drivers of the ocean carbon cycle favor a decrease of global oceanic CO_2 uptake due to climate change, there are significant differences in regional responses and their underlying mechanisms (Crueger et al., 2007; Landschützer et al., 2016). Ultimately, it is this balance between the response of land and ocean systems to future climate that will determine the strength and extent of carbon uptake by these systems and whether they might become a net source of CO_2 to the atmosphere.

19.4 Future Land Carbon Cycle

The land carbon cycle is sensitive to atmospheric composition, temperature and precipitation changes, disturbances such as fire and disease outbreaks, and land-use and land-cover changes. Future projections of the North American land carbon sink were examined using simulations from a nine-member ensemble of coupled carbon-climate models, forced with the four different future scenarios (i.e., RCPs) as described in Section 19.3, p. 763. These are the same models and RCPs that informed the *Intergovernmental Panel on Climate Change Fifth Assessment Report* (IPCC; Ciais et al., 2013).

Models estimate the strength of the mean North American net land sink from 1990 to 1999 to be 0.36 ± 0.09 Pg C per year (median ± interquartile range), which is consistent with estimates from other methods (see Ch. 2: The North American Carbon Budget, p. 71). Depending on the future scenario, model projections of net land carbon sink strength range from a slight decrease (0.21 ± 0.42 Pg C per year with RCP2.6) to a doubling (0.61 ± 0.60 Pg C per year with RCP4.5) of the current sink strength by midcentury. However, in all scenarios, the strength of the net land sink within North America is projected to either remain near current levels (e.g., RCP4.5 and RCP8.5) or decline significantly (e.g., RCP2.6 and RCP6.0) by the end of the century (see Figure 19.3, p. 772). The higher human-driven emission scenarios and/or the longer the time horizon for the projections, the more uncertain the future of the North American carbon cycle. In fact, models project that the land could be either a net sink (of up to 1.5 Pg C per year) or a net source of carbon (of up to 0.6 Pg C per year) to the atmosphere by 2100 (see Figure 19.3).

Geographically, under the two stabilization scenarios (i.e., RCP4.5 and RCP6.0), most of North America's terrestrial biosphere is projected to remain a net sink for atmospheric CO_2 through the end of the century (see Figure 19.4, p. 773). However, the strength of carbon uptake could weaken in the East and parts of the U.S. Great Plains. Under both the

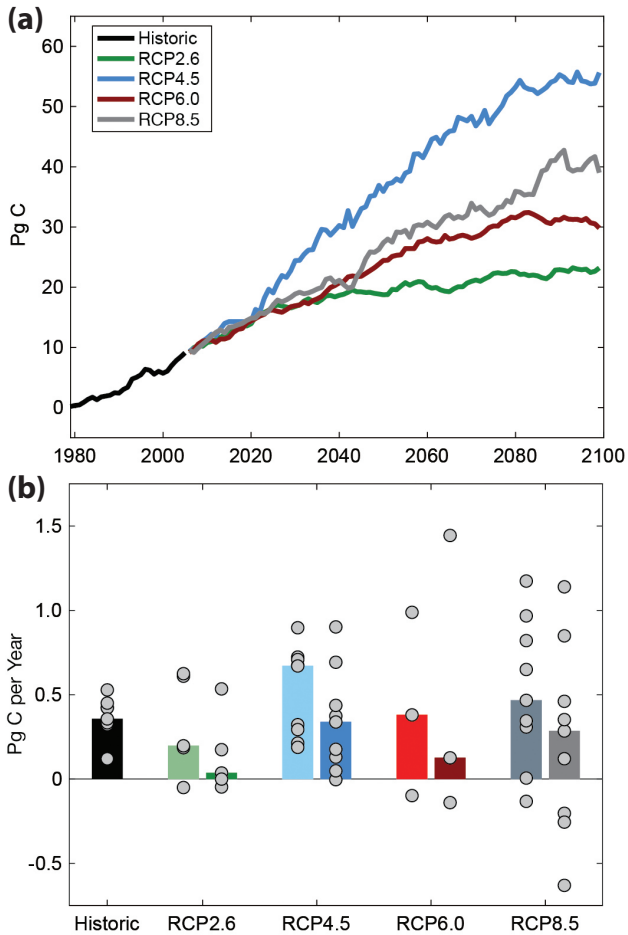

Figure 19.3. Projected Cumulative and Net Land Carbon Sink for North America Based on Four Future Scenarios. (a) Historic and projected cumulative North American land carbon sinks are shown in petagrams of carbon (Pg C) from 1980 to 2099 for the ensemble median under each Representative Concentration Pathway (RCP). **(b)** The decadal average net land carbon sink is given based on historic projections (1990 to 1999) and on two snapshots in time for each RCP: 2050 to 2059 (lighter bars on left) and 2090 to 2099 (darker bars on right). Bars show ensemble median; gray circles represent individual model projections. The number of models varies across RCP based on availability. RCP2.6 models were CanESM2, HadGEM2–ES, MIROC-ESM, MPI–ESM–LR, and NorESM1–ME. RCP4.5 and RCP8.5 models were CanESM2, GFDL-ESM2G, GFDL-ESM2M, HadGEM2–ES, IPSL–CM5A-LR, MIROC-ESM, MPI–ESM–LR, NorESM1–ME, and INMCM4. RCP6.0 models were HadGEM2–ES, MIROC-ESM, and NorESM1–ME. All models used are consistent with those from Ch. 6 of the *Intergovernmental Panel on Climate Change Fifth Assessment Report* (Ciais et al., 2013).

low and high human-driven emissions scenarios (RCP2.6 and RCP8.5), the strength of terrestrial carbon uptake is projected to weaken in much of the southern United States and in parts of northern Canada, with some temperate and northern regions turning from a net sink to a net source of CO_2 to the atmosphere (see Figure 19.4). With the exception of RCP6.0, under all scenarios, models project that both rising CO_2 and climate warming will lead to a strengthening of net carbon uptake in Alaska (see Figure 19.4). This projected net increase in carbon sink strength is due to increased net primary production in upland alpine ecosystems (Zhu and McGuire 2016), which many models project will offset increased emissions from climate warming and more frequent wildfires. However, results from a synthesis of soil warming experiments (Crowther et al., 2016) contradict these model projections, adding to the already existing large uncertainty (see Section 19.5.2, p. 778, for more details).

The combined and uncertain effects of rising CO_2, climate change, and land-use management contribute to the large range of model projections (Arora et al., 2013; Ciais et al., 2013). As discussed in Section 19.3.2, p. 766, land-use change is a key driver of carbon uptake and loss in the terrestrial biosphere. Globally, emissions related to land-use change are projected to decline with all RCPs (see Figure 19.2, p. 765), but the spatial pattern and distribution of land-use changes and their projected impacts on the North American carbon sink are not clear. In addition, local and regional ecosystems will vary considerably in their responses to changes in climate and atmospheric composition. Discussed in the next sections are key factors that will influence the sensitivity of the land carbon sink to both a warming climate and rising CO_2 and thus influence the future trajectory of North American land carbon stocks and flows.

19.4.1 Response of the Land Carbon Cycle to Rising Atmospheric CO_2

Land carbon uptake and storage are projected to increase with rising atmospheric CO_2 (via CO_2 fertilization), both globally and within North America (Ciais et al., 2013). While models tend to agree on

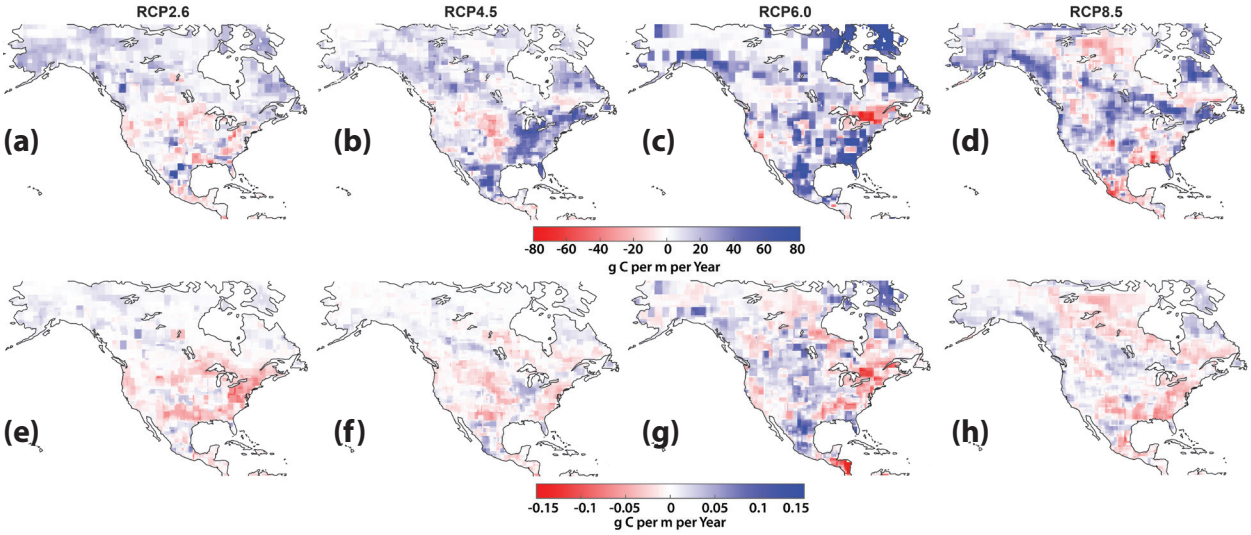

Figure 19.4. Projected Decadal Median Net Land Carbon Sink for North America Based on Four Future Scenarios. (a–d) Projected decadal median land carbon sink in grams of carbon (g C) for North America from 2090 to 2099 under each Representative Concentration Pathway (RCP) scenario: **(a)** RCP2.6, **(b)** RCP4.5, **(c)** RCP6.0, and **(d)** RCP8.5. **(e–h)** The difference between the projected net sink for each RCP and the 2000 to 2009 historic baseline, with red (negative) representing areas where the projected strength of the net sink is weaker than the historic baseline, and blue (positive) indicating areas where net carbon uptake is projected to increase compared to historic conditions. The number of models varies across RCP based on availability. RCP2.6 models were CanESM2, HadGEM2–ES, MIROC-ESM, MPI–ESM–LR, and NorESM1–ME. RCP4.5 and RCP8.5 models were CanESM2, GFDL-ESM2G, GFDL-ESM2M, HadGEM2–ES, IPSL–CM5A-LR, MIROC-ESM, MPI–ESM–LR, NorESM1–ME, and INMCM4. RCP6.0 models were HadGEM2–ES, MIROC-ESM, and NorESM1–ME. All models used are consistent with those from Ch. 6 of the *Intergovernmental Panel on Climate Change Fifth Assessment Report* (Ciais et al., 2013).

the direction of the carbon uptake response to rising CO_2, they show low agreement on the magnitude (size) of this response (see Figure 19.5, p. 775). Figure 19.6, p. 776, shows the spatial distribution of the modeled carbon sink's response to an increase in atmospheric CO_2 (see Ciais et al., 2013). The response is largest in more humid regions (e.g., U.S. Midwest and East Coast) with forested areas and greater amounts of vegetation. Whether models are correct in their projections of a sustained increase in photosynthesis by rising CO_2 (i.e., the CO_2 fertilization effect) is uncertain for a number of reasons.

First, the degree to which rising CO_2 leads to enhanced plant growth likely depends on the age distribution of trees within a forested ecosystem. Much of the evidence for a CO_2-based enhancement of ecosystem carbon storage comes from experiments (see Ch. 17: Biogeochemical Effects of Rising Atmospheric Carbon Dioxide, p. 690). Ecosystem CO_2-enrichment experiments in North American forests tend to show that, in the short term (e.g., up to 10 years), CO_2 fertilization increases forest production by 20% to 25% (McCarthy et al., 2010; Norby et al., 2005; Talhelm et al., 2014). However, most of these forest experiments are located in young forests that also were accumulating biomass under ambient CO_2 concentrations. The few experiments conducted on individual trees in more mature forests tend to show little or no growth response (Bader et al., 2013; Klein et al., 2016). Accurately projecting future CO_2 fertilization effects will likely require accounting for both the forests that already are accumulating biomass and the more established ones that are not. The different responses observed across the range of forest ages probably are related to forest interactions with other factors that limit plant production such as nitrogen availability and perhaps water.

Second, nutrients will likely constrain the land carbon cycle's response to rising CO_2 (e.g., Norby et al., 2010). Nitrogen is a key nutrient for plant growth and can limit or stimulate plant productivity and carbon uptake, depending on nitrogen availability. Nitrogen acquisition and availability probably will be a controlling factor in the strength and persistence of CO_2 fertilization (see Ch. 17: Biogeochemical Effects of Rising Atmospheric Carbon Dioxide). However, many current models do not consider nutrient cycling (Ciais et al., 2013; Hoffman et al., 2014), and models that do consider nutrient cycling exhibit substantial uncertainty in responses of terrestrial ecosystems to increased atmospheric CO_2 (Walker et al., 2015; Zaehle and Dalmonech 2011). Insights into nitrogen's complex interaction with carbon uptake are only now beginning to emerge with sufficient detail to model computationally (Drake et al., 2011; McCarthy et al., 2010; Norby et al., 2010; Terrer et al., 2016; Walker et al., 2015; Zaehle et al., 2014).

Third, the response of soil carbon stocks to rising CO_2 is uncertain. Results from some studies suggest that even if rising CO_2 does not lead to increased carbon storage in forest biomass, it may increase carbon storage in soils (e.g., Iversen et al., 2012). However, increased soil carbon input also may accelerate microbial decomposition of carbon and thus soil carbon turnover, leading to less overall soil carbon storage (Hungate et al., 2013; van Groenigen et al., 2014). The strength and magnitude of soil carbon losses, therefore, remains highly uncertain (Georgiou et al., 2015; Walker et al., 2015).

Consequently, it is unclear whether land ecosystems will truly sequester more carbon under elevated CO_2. The potential for increased photosynthesis from rising CO_2 to enhance long-term carbon storage in North American terrestrial ecosystems depends on 1) whether rising CO_2 simply intensifies the rate of short-term carbon cycling (i.e., shorter carbon residence time) or 2) whether the additional carbon is used by plants to build more wood and tissue or is stored as long-lived soil organic matter. Furthermore, variations across biomes and climatic regimes are likely, and localized extreme weather events, such as droughts or fires, can lead to a decrease in regional ecosystem carbon uptake and thus negate any expected general increases (Reichstein et al., 2013).

19.4.2 Response of the Land Carbon Cycle to a Warming Climate

Climate change is projected to partially negate expected increases in land carbon sinks caused by rising atmospheric CO_2 concentrations (see Figure 19.5, p. 775; Ciais et al., 2013; Friedlingstein 2015). Model projections of reductions in carbon storage due to climate change are primarily driven by increased decomposition of organic matter in soils in a warmer world (Friedlingstein 2015; see Ch. 12: Soils, p. 469). However, the magnitude and direction of the global and North American land carbon cycle's response to a changing climate are uncertain because of other climate warming effects. For example, warmer temperatures are projected to reduce land carbon uptake in temperate North America due to heat stress in plants and increased respiration in soils, both of which could lead to carbon losses (see Figure 19.6, p. 776). Conversely, at higher latitudes where temperature is a limiting factor, a warming climate could lengthen the growing season, leading to increased carbon storage in northern ecosystems. In addition, a warming climate can alter the water cycle through changes in precipitation patterns, snowpack, and extreme events such as droughts and floods. All these factors can alter ecosystem function and carbon cycle dynamics.

Globally, soils store 1,500 to 2,400 Pg C, more than twice the amount of carbon in the atmosphere (Bradford et al., 2016). Models project that as the climate warms, carbon losses from soils could range from minimal to significant, with up to one-third of the global soil carbon stock lost by 2100 (Bradford et al., 2016). The low confidence in these projected changes arises from several factors, including outdated assumptions about the controls on soil carbon turnover in models (i.e., model structure), uncertainty in the parameter values used to control the rate of soil carbon decomposition (i.e., model parameterization), and lack of empirical

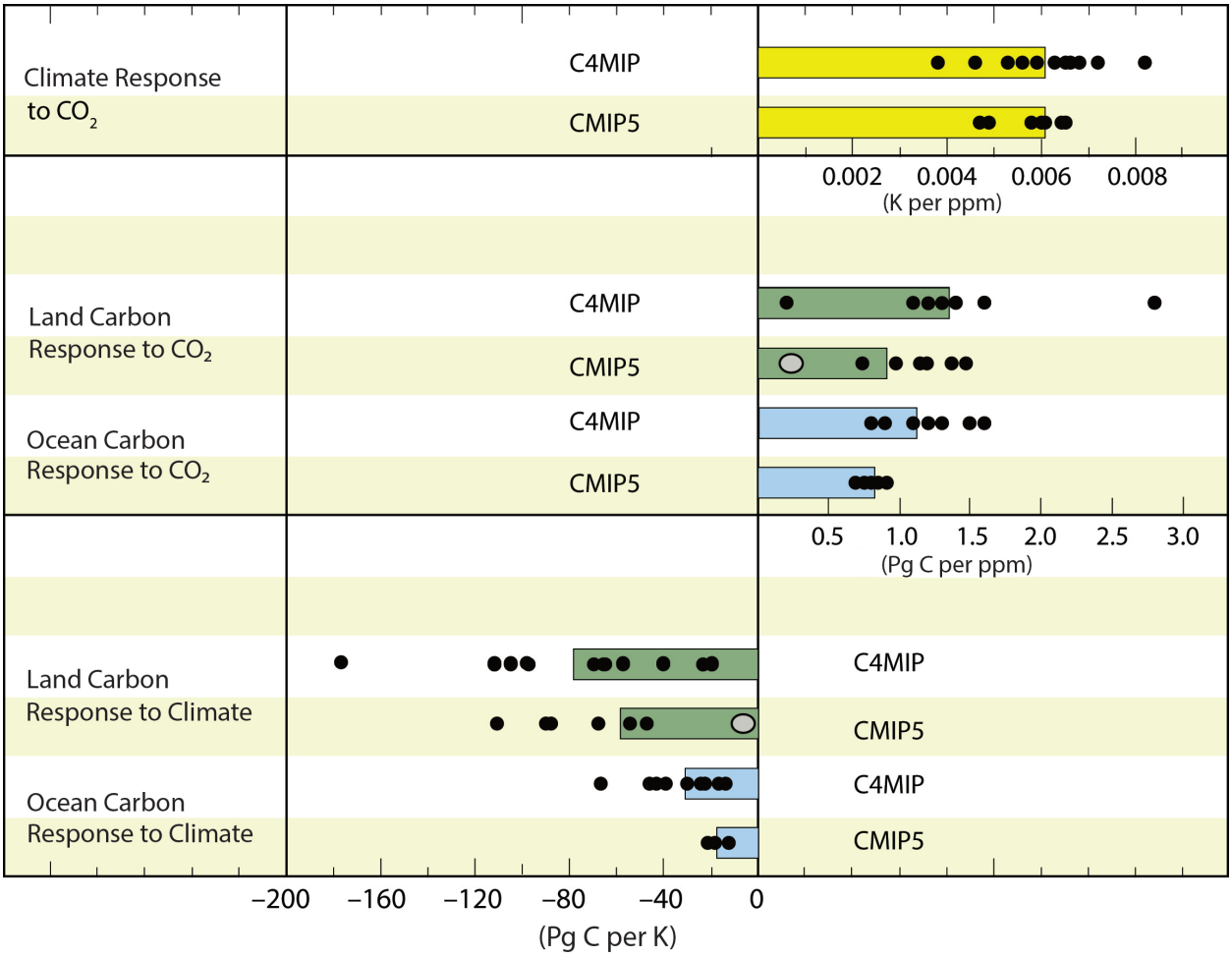

Figure 19.5. Land and Ocean Carbon Cycle Feedbacks from Two Generations of Coupled Carbon-Climate Models. The large uncertainty in carbon cycle response to climate and rising atmospheric carbon dioxide (CO_2) is shown, particularly for the land carbon cycle. Uncertainty in the response of the ocean carbon cycle to climate and rising CO_2 has decreased with model development (e.g., Coupled Climate–Carbon Cycle Model Intercomparison Project [C4MIP] and Coupled Model Intercomparison Project Phase 5 [CMIP5]), but the same cannot be said for the land carbon cycle. Key: K, Kelvin; ppm, parts per million; Pg C, petagrams of carbon. [Figure source: Reprinted from Ciais et al., 2013, copyright IPCC, used with permission.]

observations to capture long-term soil carbon dynamics (Bradford et al., 2016; Crowther et al., 2016; see Ch.12: Soils). As a result, changes in soil carbon resulting from a warming climate cannot be reliably predicted (Bradford et al., 2016). A recent study by Crowther et al. (2016) synthesized observations of warming-induced changes in soil carbon stocks from several field experiments worldwide. Their results suggest that, under business-as-usual emissions and expected climate change (i.e., 2°C increase over the next 35 years), warming could lead to a net loss of 55 ± 50 Pg C globally from surface soils by 2050. The effect of warming on soil carbon stocks varied across sites, depending on the size of the soil carbon pool and the extent and duration of warming. Their results suggest that soil carbon losses will be greatest in northern latitudes (e.g., the northeastern United States and Arctic and boreal regions of North America; see Figure 19.7, p. 777) due to the region's large soil carbon stocks and rapid rates of

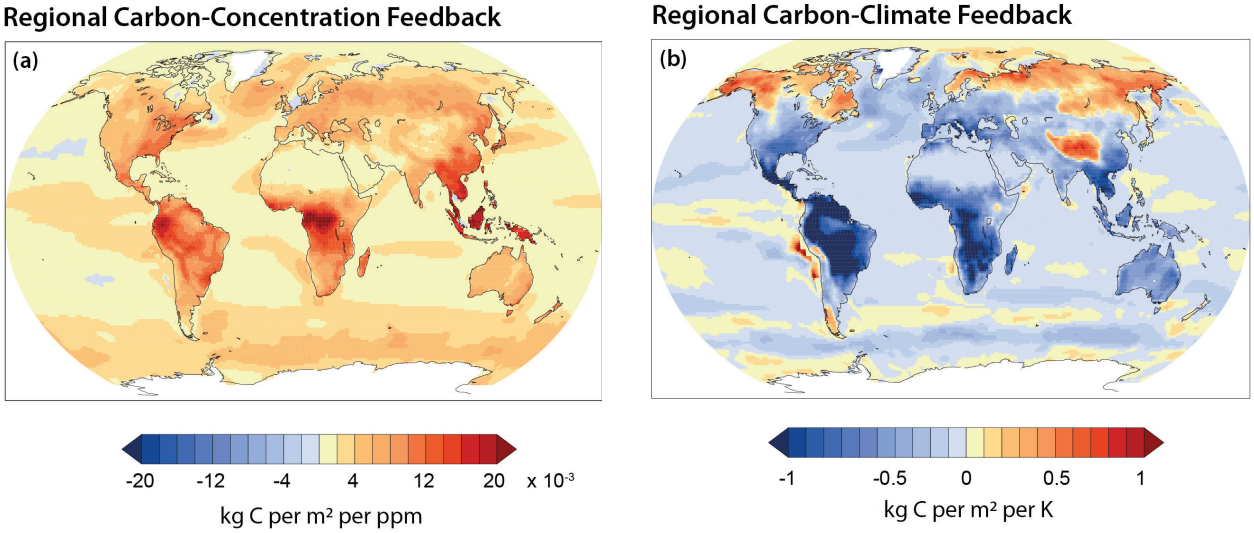

Figure 19.6. Simulated Spatial Distribution of Land and Ocean Carbon Sink Sensitivity to (a) Rising Atmospheric Carbon Dioxide (CO_2) and (b) a Warming Climate. Shows the change in land carbon storage and air-sea carbon exchange based on a quadrupling of atmospheric CO_2 concentrations relative to global CO_2 and temperature change. Based on seven models from the Coupled Model Intercomparison Project Phase 5 (CMIP5): BCC-ESM1, CanESM2, CESM1-BGC, HadGEM2-ES, IPSL-CM5a-LR, MIP-ESM-IR, and NorESM1-ME. Key: Kg C, kilograms of carbon; ppm, parts per million; K, Kelvin. [Figure source: Adapted from Figure 6.22 from Ciais et al., 2013, copyright IPCC, used with permission.]

projected warming (Crowther et al., 2016; see also USGCRP 2017a and Section 19.3.3, p. 770). The spatial distribution of potential soil carbon losses derived by Crowther et al. (2016) contradicts projections from coupled carbon-climate models used to inform the latest IPCC report (see Figure 19.6, this page). Models project that warmer temperatures and an extended growing season in high-latitude areas of North America will lead to increased plant carbon inputs to soil that will more than offset increases in soil carbon decomposition rates under warmer temperatures. However, results from warming experiments suggest the opposite—losses considerably outweigh any potential positive vegetation responses (Bradford et al., 2016; Crowther et al., 2016). The difference in modeled and experimental results could be related to how soil carbon models are configured (see Ch. 12: Soils). A number of studies point to organic-rich soils (such as wetlands and permafrost) as the carbon pools most vulnerable to climate warming (Bradford et al., 2016; Grosse et al., 2016; Koven et al., 2015; Ringeval et al., 2011; Schuur et al., 2015). However, many models do not explicitly account for permafrost dynamics and the potential carbon loss from thawing permafrost soils (Bradford et al., 2016; see Section 19.7.2, p. 780, for more details). In addition, inadequate understanding of interactive soil and plant processes and ecosystem response to climate change impedes accurate representation of soil carbon processes in current models.

19.5 Future Ocean and Coastal Carbon Cycle

The ocean continues to play a key role in mitigating climate warming by taking up most of the additional heat in the Earth system and about a third of CO_2 emissions (Gleckler et al., 2016; Frölicher et al., 2015). Short- and long-term changes in the ocean carbon cycle depend on the influences of future atmospheric CO_2, ocean temperature, and pH on CO_2 solubility, changes in ocean circulation, and carbon inputs from land, as well as the response of marine ecosystems to changes in temperature, pH,

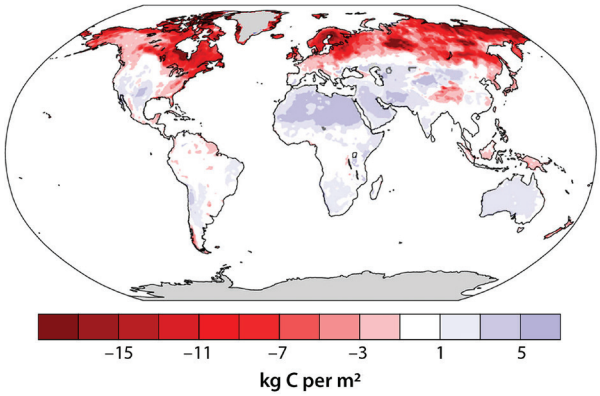

Figure 19.7. Potential Vulnerability of Soil Carbon Stocks to Climate Warming. This map, based on a meta-analysis of warming experiments, shows predicted changes in soil carbon stocks by 2050 using spatially explicit estimates of these stocks (measured in kilograms of carbon per square meter [kg C per m²]) and changes in soil surface temperature. Changes are for surface soil carbon stocks (0 to 15 cm in depth) under a 1°C rise in global average soil surface temperature. [Figure source: Reprinted from Crowther et al., 2016, copyright Macmillan Publishers Ltd, used with permission.]

and nutrient concentrations (Graven 2016; Matear and Hirst 1999; Sabine et al., 2004).

Under the United Nations Convention on the Law of the Sea (United Nations General Assembly 1982), all ocean areas within 200 nautical miles from the coast are considered exclusive economic zones (EEZs; see Ch. 16: Coastal Ocean and Continental Shelves, p. 649). Taken together, coastal areas (including EEZs) account for 41% of the global ocean area, with North America making up 10% of global coasts. Including all U.S.-inhabited territories in this estimate increases the fraction to 13% (see Ch. 16: Coastal Ocean and Continental Shelves). Connecting terrestrial and oceanic systems, coastal areas are major components of the global carbon cycle (Bauer et al., 2013; Liu et al., 2010; Regnier et al., 2013). The coastal ocean includes rivers, estuaries, tidal wetlands, and the continental shelf; carbon flows within and between these coastal subsystems are substantial (Bauer et al., 2013). Over the past 50 to 100 years, a variety of human activities have shifted the global coastal ocean from being a net source to a net sink of carbon (approximately 0.45 Pg C annually) from the atmosphere (Bauer et al., 2013). However, because carbon processing within coastal systems varies widely in space and time, estimates of carbon flows within and between coastal subsystems are uncertain (Bauer et al., 2013).

Projections from three CMIP5 models—GFDL-ESM2M (Dunne et al., 2013), HadGEM-ESM (Martin et al., 2011), and MIROC-ESM (Watanabe et al., 2011)— were used to estimate a range of historical (1870 to 1995) and future anthropogenic carbon uptake within North American EEZs (about 22.5×10^6 km^2). Since 1870, North American EEZs have taken up 2.6 to 3.4 Pg C of anthropogenic carbon. Under the highest emissions scenario (RCP8.5), these regions are projected to take up an additional 10 to 12 Pg C by 2050 and another 17 to 26 Pg C in the second half of this century (2050 to 2100). Climate warming, changing circulation, and acidification are expected to present new pressures for ocean and coastal carbon systems. Great uncertainty persists around projected changes in coastal carbon cycling as atmospheric CO_2 rises, challenging quantification of air-sea CO_2 fluxes and efforts to detect and attribute these changing fluxes at the regional coastal scale (Lovenduski et al., 2016). Although coastal zones may be sinks for carbon in the postindustrial age, they are so heavily influenced by human activities and terrestrial processes that projecting their future carbon sink or source behavior is difficult (Bauer et al., 2013).

19.5.1 Response of the Ocean and Coastal Carbon Cycle to Rising Atmospheric CO_2

Within North America, rising atmospheric CO_2 is projected to increase ocean and coastal carbon uptake almost everywhere, particularly in the North Atlantic, which shows the strongest uptake response (see Figure 19.5, p. 775). Rising atmospheric CO_2 concentrations have changed the chemical partitioning of CO_2 between the atmosphere and ocean, driving more CO_2 into the ocean. While the surface ocean (top 50 m) comes into CO_2 equilibrium with the atmosphere on the timescale of years, equilibrium with the deeper, interior ocean depends on

circulation and ventilation with the atmosphere, a process that varies from years to millennia. As such, most of the ocean is not in equilibrium with the present-day atmosphere. Thus, current rates of CO_2 emissions from fossil fuel burning are guaranteed to continue ocean warming and acidification (Joos et al., 2011) in the coming decades because of the imbalance between atmospheric CO_2 levels and ocean CO_2 uptake capacity.

As seawater takes up atmospheric CO_2 and heat, its buffering capacity decreases as part of ocean acidification (Egleston et al., 2010; see also Ch. 17: Biogeochemical Effects of Rising Atmospheric Carbon Dioxide, p. 690). In the future, warmer and more CO_2-enriched waters are expected to take up less additional CO_2 and be less resistant to changes in pH (Ciais et al., 2013). Models project that under business-as-usual CO_2 emissions (RCP8.5), seawater pH is likely to decrease 0.4 to 0.5 pH units by 2100 in the ocean basins bordering North America (Bopp et al., 2013). Conversely, with reduced human-driven CO_2 emissions intended to limit global surface temperature increase to 2°C (RCP2.6), seawater pH in North America's surrounding ocean basins would likely drop about 0.1 pH unit (Bopp et al., 2013). Furthermore, changes in ocean circulation (e.g., weakening of the Atlantic meridional overturning circulation; Stouffer et al., 2006) will reduce the vertical transport of carbon into deep ocean layers, thus decreasing the current level of uptake in the North Atlantic. Another mechanism of additional carbon sequestration may occur through enhancement of sinking organic carbon from the surface and subsequent remineralization of this carbon at depth. Under future conditions, models show that phytoplankton and zooplankton populations are likely to shift toward groups that favor higher temperature, greater physical stratification, and elevated CO_2 conditions (Bopp et al., 2013; Doney et al., 2009), both in terms of trait diversity within groups (e.g., Dutkiewicz et al., 2013) and in some groups being favored over others (e.g., slow growing, CO_2-limited nitrogen fixers; Hutchins et al., 2007). However, knowledge is lacking on the total effects these population shifts will have on mechanisms such as grazing and aggregation that create sinking material and other biogeochemical cycle changes that may indirectly influence carbon cycling and sequestration (e.g., the nitrogen cycle).

19.5.2 Response of the Ocean and Coastal Carbon Cycle to Warming Climate

Contrary to the effects of rising atmospheric CO_2 alone, a warming climate is projected to reduce ocean and coastal carbon uptake in most regions within North America (see Figure 19.5, p. 775). Atmospheric and oceanic warming are projected to increase stratification and slow midlatitude ocean circulation (Vecchi and Soden 2007), decreasing CO_2 uptake rates (Schwinger et al., 2014). For example, a reduction in ocean carbon uptake has been linked to a decrease of meridional ocean circulation, convective mixing, and increased stratification in the high latitudes (Matear and Hirst 1999). The impacts, however, are uniquely regional (Crueger et al., 2007), as exemplified in the California Current system where climate warming is expected to shift the upwelling region poleward (Rykaczewski et al., 2015). Along the eastern mid-Atlantic shelf, waters may preferentially warm with the poleward shift in winds and current intensification (Wu et al., 2012). These changes may modify the waters' ability to take up carbon and modulate the latitudinal extent of natural CO_2 outgassing and uptake of atmospheric CO_2 along the coast. Both the St. Lawrence estuary bottom waters (Gilbert et al., 2005) and Southern California Bight interior waters (Bograd et al., 2008) have experienced decreases in oxygen content and commensurate increases in the sequestration of remineralized carbon after it sunk from the surface in response to multidecadal climate change. Additional examples of changes in coastal carbon storage and processing and projected changes are provided in Ch. 15: Tidal Wetlands and Estuaries, p. 596.

Climate-driven warming and changes in precipitation also may have major impacts on the amount (Georgakakos et al., 2014) and composition (Tranvik and Jansson 2002) of future river carbon fluxes

into coastal systems. Extreme rainfall and flooding events associated with a changing climate will likely lead to a shift in the timing of carbon delivery to the coastal ocean from terrestrial systems, affecting coastal carbon budgets in the future (Bauer et al., 2013). Enhanced physical erosion due to the increased occurrence of extreme precipitation events may export more particulate organic carbon to the coastal zone, and burial rates of this organic carbon will influence coastal carbon sequestration (Galy et al., 2015). Enhanced erosion is also expected to result from rising sea levels, significantly altering carbon cycling in coastal estuaries in general and wetlands (Kirwan and Megonigal 2013), mangroves (Bouillon et al., 2008), and seagrass beds (Fourqurean et al., 2012) in particular.

Coral reef ecosystems are particularly sensitive to the combination of warming and acidification (Hoegh-Guldberg et al., 2007). In today's ocean, the formation of calcium carbonate in coral reefs has resulted in a significant loss of alkalinity and buffering capacity. As coral calcification decreases, these ecosystems may shift from removing ocean buffering capacity to supplying it. Similarly, thawing permafrost in the Arctic is expected to release organic carbon whose degradation by microbes is projected to create a positive feedback to climate change (Schuur et al., 2008; see also Ch. 11: Arctic and Boreal Carbon, p. 428).

Oceanic and coastal systems clearly are continuing to respond to myriad natural and human-driven changes, although long-term variations or the mechanisms influencing them are unclear. These systems remain a high-priority study area for both the North American and global carbon science communities to better understand the vulnerability of the ocean carbon sink to rising levels of atmospheric CO_2 and future climate change.

19.6 Future Freshwater Carbon Cycle

Inland waters occupy a small fraction of Earth's surface, yet they play a major role in the global carbon cycle (Biddanda 2017; Buffam et al., 2011; see Ch. 14: Inland Waters, p. 568). Intrinsically linked to human activities, inland water ecosystems are active, changing, and important regulators of carbon cycling and climate (e.g., Tranvik et al., 2009). These freshwater systems export considerable amounts of carbon from adjacent terrestrial environments to the ocean while also burying organic carbon in inland water sediments (Bauer et al., 2013). In fact, the global burial of organic carbon in these sediments exceeds organic carbon sequestration on the ocean floor (Aufdenkampe et al., 2011; Battin et al., 2009; Tranvik et al., 2009). A synthesis by Tranvik et al. (2009), with a particular focus on North America, demonstrated that global annual CO_2 emissions from inland waters (e.g., lakes, impoundments, streams, and rivers) to the atmosphere are similar in magnitude to the amount of atmospheric CO_2 taken up by the ocean annually. Although most lakes and rivers across a range of latitudes are reported sources of CO_2 to the atmosphere (Alin and Johnson 2007; Cole et al., 2007), there is considerable regional and seasonal variability on the role of freshwater systems as net carbon sources or sinks due to differences in system size, total amount of biomass, carbon residence time, and geological and geographical setting. In North America, most studies show that Lake Superior, Lake Michigan, and Lake Huron are CO_2 sources annually, while Lake Erie and Lake Ontario are slight CO_2 sinks (McKinley et al., 2011).

The role of freshwater systems in the carbon cycle and as climate regulators has changed dramatically over the years. There is high confidence that climate-induced changes in precipitation, hydrological patterns, flow and thermal regimes, and watershed characteristics will significantly affect freshwater ecosystems and their role in carbon cycling (Settele et al., 2014). Model projections of surface and bottom water temperatures of lakes, reservoirs, and rivers throughout North America consistently show an increase from 2°C to 7°C based on climate scenarios where CO_2 doubles (e.g., Fang and Stefan 1999; Gooseff et al., 2005; Lehman 2002). This warming is likely to extend and intensify thermal stratification in lakes, resulting in oxygen deficiency and increasing organic carbon sequestration and

burial while favoring methanogenesis and enhanced CH_4 emissions from lakes (Romero-Lankao et al., 2014; Tranvik et al., 2009; Wilhelm and Adrian 2007). Freshwater systems at high altitude and high latitude, including alpine and Arctic streams and lakes, are particularly vulnerable to direct climate effects, especially rising temperatures (Settele et al., 2014). Warming and decreased ice cover at high latitudes are expected to affect lake stratification and mixing regimes (Vincent 2009). These factors could shift some northern hardwater lakes from being substantial sources to net sinks of atmospheric CO_2. Reduced ice cover also can decrease CO_2 accumulation under the ice, increasing spring and summer pH and enhancing the chemical uptake of CO_2 (Finlay et al., 2015). Campeau and Del Giorgio (2014) suggested that the current role of boreal fluvial networks as major landscape sources of carbon (CO_2 and CH_4) is likely to expand with climate change, mainly driven by large increases in fluvial CH_4 emissions in response to changes in water temperature and in-stream metabolism. Based on CO_2 doubling scenarios from several global circulation models, water levels in the Great Lakes are expected to decline and the frequency of intense storm events is expected to increase. These events, along with warmer water temperatures, are projected to alter the timing and quality of runoff and nutrient loading, change light conditions, and increase lake stratification (Angel and Kunkel 2010; Jiménez Cisneros et al., 2014; Watson et al., 2000), consequently affecting primary production and respiration rates.

19.7 Synthesis, Knowledge Gaps, and Key Research Needs

By absorbing atmospheric CO_2, the land and ocean play an important role in slowing the buildup of GHGs in the atmosphere, thereby slowing the pace of climate change. As mentioned at the outset of this chapter, an important question in carbon cycle science is whether ocean and land systems will continue to provide this service or whether the strength of the ocean and land carbon sink will decrease under changing climate conditions (Michalak et al., 2011). Numerous vulnerabilities are associated with assessing current and projected carbon cycle conditions. Taking into account the magnitude, timing, and likelihood of projected carbon cycle changes discussed in this chapter, this section synthesizes current understanding, highlighting critical carbon cycle vulnerabilities, knowledge gaps, and key research needs related to the co-evolution of carbon cycle dynamics in a changing climate.

19.7.1 CO_2 Fertilization

Crucial to projecting future changes in the North American carbon cycle is the ability to project the response of land ecosystems to increasing atmospheric CO_2. As discussed in Section 19.4.1, p. 772, three areas of incomplete understanding limit current efforts to project forest and terrestrial ecosystem responses to increasing CO_2: 1) age distribution of forests, 2) nutrient interactions (particularly nitrogen), and 3) soil carbon responses. These three areas are interrelated because of a lack of understanding about carbon-nitrogen coupling. More research is needed to understand what constitutes plant nitrogen demand, carbon-allocation strategies used by plants to respond to nutrient demand, the carbon cost of nitrogen acquisition, factors that determine the capacity of soils to supply nitrogen, and soil carbon losses associated with increased soil nitrogen mineralization.

19.7.2 Permafrost Carbon–Climate Feedback

A primary uncertainty in carbon-climate feedback projections stems from limited understanding of the responses of carbon stocks in the northern high latitudes (≥60°N) to a changing climate. Estimates show that, globally, surface permafrost (0 to 3 m) contains about 33% of the overall surface soil carbon pool (1,035 ± 150 Pg C; Hugelius et al., 2014). Along with carbon deposits deeper than 3 m (including those within the Yedoma region) and subsea permafrost carbon, the total estimate of terrestrial permafrost carbon in the northern permafrost zone is 1,330 to 1,580 Pg C (Schuur et al., 2015). More recent simulations (McGuire et al.,

2018) estimate that between 2010 and 2299, losses of permafrost between 3 and 5 million km^2 for the RCP4.5 climate and between 6 and 16 million km^2 for the RCP8.5 climate may be possible.

The permafrost zone's overall carbon budget is determined by the soil carbon as well as vegetation carbon dynamics and their interactions. For example, increased vegetation growth due to warming leads to greater soil carbon inputs, whereas permafrost thawing accelerates carbon release (see Ch. 11: Arctic and Boreal Carbon, p. 428). The presence of large carbon stocks in a rapidly warming region raises concern about increased carbon emissions, as well as changes in global albedo, the hydrological cycle, and thermohaline circulation (Hinzman et al., 2013).

The primary challenge in projecting the trajectory of permafrost thawing is that the physical and biogeochemical properties of permafrost vary widely depending on the characteristics of the parent material, ice and liquid water content, topography, biota, and climate (Jorgenson et al., 2010). With continued warming and large-scale losses of near-surface permafrost, almost all terrestrial carbon cycle models indicate that by the end of this century, the Arctic could shift from a net sink to a source of carbon (Cox et al., 2000; Fisher et al., 2014b). Considerable debate remains, however, on the amplitude, timing, and form of the carbon release (e.g., Lenton et al., 2008; Schuur et al., 2015; Slater and Lawrence 2013). This disagreement is directly related to a lack of understanding of three key factors that determine the potential climate feedback of the permafrost carbon pool: 1) area and depth of permafrost vulnerable to release, 2) the speed with which carbon will be released from thawing soils, and 3) the form of carbon (e.g., CO_2 or CH_4) that will be released (NRC 2014). Similar to land permafrost, questions have emerged about the stability of organic carbon sequestered in the marine permafrost of Alaska and Canada amid climate warming (see Section 19.7.4, p. 783). Combined, these limitations in understanding result in considerable uncertainty in how future climate change will affect northern high latitudes and reshape traditional ways of life. Ongoing research efforts led by U.S., Canadian, and international partners have highlighted the need for long-term empirical observations to capture soil carbon dynamics to improve understanding of land carbon–climate feedbacks and evaluate model performance, thereby constraining future projections.

19.7.3 Disturbance

Fire and Disease

Natural and human-driven disturbances will influence future vegetation carbon storage. Forest disturbance is a fundamental driver of terrestrial carbon cycle dynamics (Hicke et al., 2012), and harvesting, fire, wind throw, storms, pathogen and pest outbreaks, and drought collectively lead to the removal of 200 Tg C from U.S. forests annually (Williams et al., 2016). Initially, most disturbances shift an ecosystem to a carbon source, while recovery from disturbance is commonly associated with greater net ecosystem carbon storage (Magnani et al., 2007; Odum 1969). Hence, disturbance effects on carbon balance in forests are both immediate and lagged and potentially long lasting. Given current management practices, climate change is likely to increase the frequency and intensity of ecological disturbances across multiple spatial and temporal scales (Running 2008). For example, reduced water availability resulting from decreased precipitation and snowpack probably will increase forest susceptibility to fire and insect attack (Allen and Breshears 1998; Breshears et al., 2009; Westerling et al., 2006).

Fire activity is largely expected to increase (Sommers et al., 2014; Westerling et al., 2006) in many regions, with fire seasons starting earlier and ending later compared to previous decades (Jolly et al., 2015). Uncertain, however, is whether regional fire severity will decrease or increase (Collins 2014; Fried et al., 2004; Parks et al., 2016; Stavros et al., 2014) by mid-century. In the western United States specifically, projected increases in fire activity (Westerling et al., 2006) imply a decrease in biomass accumulation between successive fires, resulting in less biomass available for combustion and, thus, a reduction in fire severity. A recent study by Parks et al. (2016)

also points out that projected increases in water stress will decrease productivity in the generally water-limited western United States, which may also feedback to further reduce the amount of biomass available to burn. However, since changes in fire–carbon cycle linkages are highly ecosystem specific, temperature-limited forests (e.g., northern high latitudes)—unlike the water-limited forests of the western United States—will likely experience increased fire frequency and severity under a warmer climate (Kasischke et al., 2010).

The extent and severity of forest insect disturbances has increased with changing climate conditions (Kurz et al., 2008). As climate warms, the range of insects (e.g., mountain pine beetle) has expanded into higher elevations and latitudes, putting previously unaffected forests at risk (Bentz et al., 2010; Kurz et al., 2008). Combined, these changes in disturbance regime and severity may result in significant loss of forest carbon sinks, particularly in North America as live carbon stocks transition to dead (Hicke et al., 2012; Kurz et al., 2008). However, the timing of carbon release associated with forest insect disturbances is unclear because of uncertainty surrounding respiration suppression or enhancement (Borkhuu et al., 2015; Levy-Varon et al., 2014; Moore et al., 2013); specific biogeochemical, microbial, and hydrological responses (Edburg et al., 2012; Maurer et al., 2016; Trahan et al., 2015); and the overall ecosystem carbon balance (Ghimire et al., 2015). Losses of carbon stocks caused by disturbance are mediated by interactions among climate, vegetation type, and productivity, with changing forest management practices resulting in reduced potential fuel loads and thus reductions in fire severity (Parks et al., 2016).

Drought

Similar to fire and insect infestations, droughts can trigger immediate and time-lagged effects on carbon stocks and flows (van der Molen et al., 2011). Both seasonal short-term observations and modeling studies have documented the effects of drought on ecosystem carbon fluxes (Anderegg et al., 2012, 2015; Ciais et al., 2005; Doughty et al., 2015; Keenan et al., 2009; Zeng et al., 2005). Over the last decade, midlatitudes in the United States have experienced frequent drought events, and similar events are expected to increase in area, frequency, intensity, and duration (e.g., Blunden et al., 2011; Kogan et al., 2013; USGCRP 2017a). Although early prediction and detection of water-induced vegetation stress are critical for agribusiness and food security (Jones et al., 2011), the exact coupling between the carbon and hydrological cycles remains unclear, as does the response of different vegetation types to short-term water stress. For example, the impact of the 2012 summer drought in the United States was compensated by increased spring carbon uptake due to earlier vegetation activity (Wolf et al., 2016); these two opposing effects mitigated the impact on the net annual carbon uptake for 2012. Is the response observed in 2012 representative of what can be expected under future climate change? The answer to this question remains highly uncertain. Climate projections from the CMIP5 ensemble of model simulations show warmer spring and drier summer mean conditions across the United States similar to those observed in 2012. Additionally, drought-induced near-term changes in plant water content can have a longer-term impact by increasing an ecosystem's vulnerability to other disturbances, such as wildfire and insect outbreaks (Arnone et al., 2008; Reichstein et al., 2013; van Mantgem et al., 2009). Thus, future projections of carbon cycle vulnerability due to drought need to adopt a holistic modeling framework to assess the full range of responses to climate extremes.

Land-Use and Land-Cover Changes

Understanding the carbon cycle effects of changes in land-use and land-cover (LULC) management requires insights into diverse issues and processes. These include the socioeconomic factors (e.g., technological change and market incentives) driving human use of land, as well as the biophysical (e.g., albedo, evaporation, and heat flux), biogeochemical (e.g., carbon and nutrient cycling), and biogeographical processes (e.g., location and

movement of species) affected by land-use choices. For example, intensive agriculture in the western United States appears to have caused abrupt losses of Arctic ecosystem structure and soil erosion (carbon cycling) due to increased populations of migrating snow geese supported by agricultural food supplies (Jefferies et al., 2006; MacDonald et al., 2014). Such dynamic interconnectivity and coupling between natural and human-driven activities at different space-time regimes demonstrate the challenge in projecting long-term feedbacks between the carbon cycle and land use.

As discussed in Section 19.3.2, p. 766, generating estimates of future potential LULC management and change is challenging because of the difficulty in projecting not only dynamics within and between complex terrestrial ecosystems, but also future potential climate, macroeconomic, and social conditions. Moreover, many of these conditions can vary significantly, depending on location and the temporal and spatial scales of the analysis. Policies and programs can significantly affect land use, especially on public lands, whereas market signals can have a large impact on how private lands are used. For example, the role of markets is important as landowners make decisions affecting LULC management, which in turn affects GHG emission levels, ensuing climate change, and thus carbon cycles. As a result, there is relatively high variability in projected estimates of land-cover change and associated impacts on carbon stocks and net emissions (Buchholz et al., 2014). Additional research is needed to model existing trends in land management and to develop scenarios of future land management and associated changes in carbon stocks and emissions (USGCRP 2017b).

19.7.4 Ocean and Coastal Carbon Cycles

Key uncertainties in processes that affect carbon cycling in the ocean and coastal zones limit the ability to project future system responses. Often highly populated, coastal zones have diverse uses as residential, urban, industrial, shipping, and recreational areas, resulting in a complex interplay of management drivers. Management of coastal wetlands, mangroves, and seagrass beds amid sea level rise, in particular, will have important carbon cycle consequences because these systems sequester carbon with extremely high efficiency and would be replaced by other systems whose sequestration efficiency is much lower. Natural disturbances commonly responsible for the loss of carbon-intensive ecosystems include hurricanes, earthquakes, disease, and herbivore grazing. The human activities most affecting these coastal ocean ecosystems are nutrient and sediment loading from runoff and sewage disposal, dredging and filling, pollution, upland development, and certain fishing practices such as trawling (Short and Wyllie-Echeverria 1996). Although activities such as dredging of shipping channels and erosion-control measures can have locally strong implications, more regionally expansive activities such as bottom trawling may have important coastal carbon cycle effects, depending on trawling intensity and bottom biogeography (e.g., Duplisea et al., 2001).

Changes in sedimentary carbon processing due to warming, acidification, or deoxygenation will alter the source and sink status of coastal zones, which already are insufficiently understood. Continued human disturbance of coastal zones represents an added perturbation to biological production and respiration both in the water column and in sediments, with the potential to substantially alter existing and also poorly understood coastal carbon cycling. Microbial regeneration of organic matter under warming, deoxygenation, and acidification may change as well, altering the timing, magnitude, or locations of CO_2 release back into seawater. Vertical export of carbon via the creation of sinking material such as fecal pellets and marine snow (Alldredge and Silver 1988) is still poorly understood and parameterized in many models. In addition, the physiological and ecosystem impacts previously outlined (e.g., changes in grazing or recycling) also may influence how much carbon is sequestered to the deep ocean by vertical export (Marsay et al., 2015). Finally, compared to terrestrial systems, there is only rudimentary understanding of ocean and coastal system resilience to climate- or carbon-driven perturbations

and the speed with which they may recover from short-term disturbances under climate change.

High-latitude coastal ecosystems are among those most likely to experience an amplification of global change (e.g., Serreze and Francis 2006). Along with significant increases in river discharges in the past century, most of the coastline in the northern high latitudes is receding at an unprecedented rate due to coastal erosion, mobilizing large quantities of sediments and carbon. Estimates of the biogeochemical processes, interactions, and exchanges across the land-ocean interface in this region are still poorly constrained. Detailed studies have examined specific aspects of individual northern, high-latitude rivers including the Yukon (Dornblaser and Striegl 2009; Spencer et al., 2008) and Mackenzie (e.g., Emmerton et al., 2008). However, only a few studies have assessed how these riverine fluxes directly affect the coastal ecosystems from river deltas to estuaries on larger regional scales (e.g., Dittmar and Kattner 2003) and longer-term decadal timescales (e.g., Overeem and Syvitski 2010).

19.7.5 Freshwater Carbon Cycle

Freshwater ecosystems are particularly vulnerable to anthropogenic disturbances and are considered to be among the most threatened ecosystems on the planet (Vorosmarty et al., 2010). Human activities such as water management, river fragmentation by dams, alteration of natural flow, construction of water impoundments, and changes in land use have a major impact on freshwater ecology, biology, and carbon cycling. There is high confidence that direct human impacts will continue to dominate the threats to most freshwater ecosystems globally over the next three decades as urbanization increases, irrigated agriculture expands, and human demand for water resources grows (Settele et al., 2014). The high connectivity between lakes and their catchments suggests that future CO_2 concentrations in lakes and exchanges with the atmosphere will be highly sensitive to altered catchment management and effects of climate change on catchment characteristics (Maberly et al., 2012). Projected increases in human-driven nutrient inputs, from either watershed or airshed processes (Rabalais et al., 2009), are expected to enhance inland water primary production and biological uptake of atmospheric CO_2 (Pacheco et al., 2014). Acidification may put additional ecological pressure on freshwaters (Hasler et al., 2016; Phillips et al., 2015; Weiss et al., 2018), thus further confounding the impacts. Similarly, concomitant increases in organic carbon inputs and intensification of mineralization could offset increased CO_2 uptake in many of these systems (Jansson et al., 2008).

Projecting the response of freshwater systems to future environmental change will require accounting for differences across systems and climatic regimes. Also needed are projections that include the complex interactions between climate change and the many natural and human-driven stressors that affect inland ecosystems. Key uncertainties exist in the mechanistic understanding of carbon sources, lability, and transformations taking place in inland waters. To better predict freshwater systems, improved coupled hydrodynamic-biogeochemical models are needed, along with new remote-sensing tools and sensors with high spatial and spectral resolution for capturing the broad spatiotemporal variability that characterizes freshwater carbon fluxes.

Finally, it is worth underscoring that significant knowledge gaps remain in current understanding of the future trajectory of North American carbon storage in terrestrial and aquatic ecosystems, permafrost carbon-climate linkages, and the role of natural and human-driven disturbance on carbon cycling dynamics. These and other impacts, vulnerabilities, and risks are recognized as meriting attention and research. For all these emerging research areas, a combination of observational, experimental, synthesis, and modeling activities is needed to gain a predictive understanding of these processes (see Box 19.2, Improving Model Projections of Future Carbon Cycle Changes, p. 785), and thereby better constrain the future of the North American (and global) carbon cycle.

Box 19.2 Improving Model Projections of Future Carbon Cycle Changes

Laboratory and controlled field experiments, along with satellite remote sensing and intensive airborne observations, provide clues about carbon-climate interactions and guide understanding of potential future responses of the carbon cycle to changing atmospheric and climate conditions. However, climate and carbon cycle interactions are more temporally dynamic and spatially diverse than field studies can adequately sample. Furthermore, carbon cycle feedbacks with climate cannot be directly observed or measured due to the long timescales involved (Friedlingstein 2015). As a result, projections of future carbon cycle behavior amid changing climate and environmental conditions rely mostly on information available from a variety of carbon and Earth System Models.

Models are integral components of carbon cycle science. One value of using models to simulate the carbon cycle and its response to environmental drivers and human factors is that models can simulate not only current conditions, but also a range of potential future conditions or realities (Fisher et al., 2014a). Models can be used to project potential carbon cycle changes resulting from different human-caused emission pathways (see Section 19.3.1, p. 765), different management or policy choices (see Section 19.3.2, p. 766), and different climate scenarios (see Section 19.3.3, p. 770). Thus, models can be used to improve understanding of the potential land and ocean ecosystem response to changing environmental conditions and to identify potential tipping points or thresholds in the carbon cycle.

Modeling carbon cycle dynamics poses a variety of challenges, however, which lead to uncertainties in projections. Three key sources of error are discussed that contribute to uncertainties in carbon cycle projections:

1. **Model Inputs.** Carbon cycle processes are highly sensitive to environmental change. Thus, uncertainty in these external forcings or future scenarios can lead to biases in model projections (Luo et al., 2015). In historic simulations (e.g., up to the present day), the choice of data used as input to a model can influence model results. For example, Poulter et al. (2011) found that the choice of land cover and climate data selection impacted simulated net primary production by up to 13% and soil respiration by up to 19%. In addition, Huntzinger et al. (2013) found that using consistent environmental driver data among models could lower model spread considerably. In future model projections, uncertainties in the forcing scenarios and time evolution of greenhouse gas emissions, land use, and other human-driven activities can lead to considerable uncertainty or variability in forecasts (Bonan and Doney 2018), particularly in predictions of future ocean carbon cycling.

2. **Model Structure.** To simulate carbon cycle responses to global change as realistically as possible, models have incorporated increasingly relevant processes (e.g., Fisher et al., 2014b). Continued improvements to the model structure are critical to advance both theoretical understanding of the driving biogeochemical processes and the accuracy of carbon cycle projections (Anav et al., 2013). However, the more processes a model incorporates to realistically simulate real-world phenomena, the more difficult it becomes to understand or evaluate the model's complex behaviors and the interplay among processes. As a result, uncertainty in projections among models cannot be easily diagnosed and

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attributed to underlying sources (e.g., Luo et al., 2009). Model intercomparison efforts are an effective way to help diagnose differences among groups of sophisticated models (e.g., Multi-scale Synthesis and Terrestrial Model Intercomparison Project [MsTMIP; Huntzinger et al., 2013, 2017], TRENDY [Piao et al., 2013], and Vegetation/Ecosystem Modeling and Analysis Project [VEMAP; Melillo et al., 1995]). Despite these advances, the current generation of models still clearly suffers from incomplete process representation, especially related to carbon dioxide fertilization response (see Section 19.7.1, p. 780); permafrost (see Section 19.7.2, p. 780); disturbance-related carbon dynamics (see Section 19.7.3, p. 781); and interactions among tidal wetlands, estuaries, sediments, and shelf waters (Benway et al., 2016; see also Ch. 15: Tidal Wetlands and Estuaries, p. 596).

3. **Model Parameterization.** The ways in which processes are represented within models are informed by carbon cycle observations. Existing observations span only a limited subset of spatial and temporal scales, however, leading to additional uncertainties. Developing approaches for using a broader array of available observational datasets (see Appendix C: Selected Carbon Cycle Research Observations and Measurement Programs, p. 821) could help in revising current modeling approaches and informing model parameterizations. For example, optimized calibration of model parameters with common databases through data assimilation (Forkel et al., 2014; Hararuk et al., 2014; MacBean et al., 2016; Smith et al., 2013) could substantially reduce systematic biases among models and provide information about underlying processes that control carbon dynamics. Achieving these advancements requires a) improving the availability and use of global databases (Bloom and Williams 2015), b) developing carbon cycle data systems that can effectively assimilate both flux- and pool-based datasets into global carbon cycle models (Bacour et al., 2015), c) understanding subgrid-scale variability of model parameters, and d) increasing the overall computational efficiency of the optimization process.

Combined, model structure and model parameterization constitute what is termed "model uncertainty," or uncertainty in the model itself, whereas uncertainty from input data, forcing scenario, or natural variability are external to the model's representation of the biosphere. The contribution of each of these uncertainty sources to a given projection depends on the spatial scale, time horizon, and quantity of interest (Bonan and Doney 2018; see Figure 19.8, p. 787). In projections of cumulative global carbon uptake from 2006 to 2100, model uncertainty and scenario uncertainty contributed most to the spread of projections across the ensemble of models (see Figure 19.8). Projections of the future ocean carbon cycle are dominated by scenario uncertainty by the end of the century, whereas projections of the land carbon cycle are attributed mostly to model structure.

To reduce model uncertainty related to the model itself (i.e., model structure and parameterization), model performance must be critically evaluated against observations. A host of recent studies (e.g., De Kauwe et al., 2013, 2014; Luo et al., 2012; Medlyn et al., 2015; Sulman et al., 2012; Walker et al., 2015; Zaehle et al., 2014) offer a promising set of techniques for diagnosing model variability (e.g., the International Land Model Benchmarking project [ILAMB; Hoffman et al., 2017] for the land carbon cycle and the Coastal CARbon Synthesis [CCARS; Benway et al. 2016] for North American estuarine and tidal wetlands). To enable more comprehensive model evaluations in the next few years, both the list of output variables and focus areas (e.g., ocean and coastal carbon

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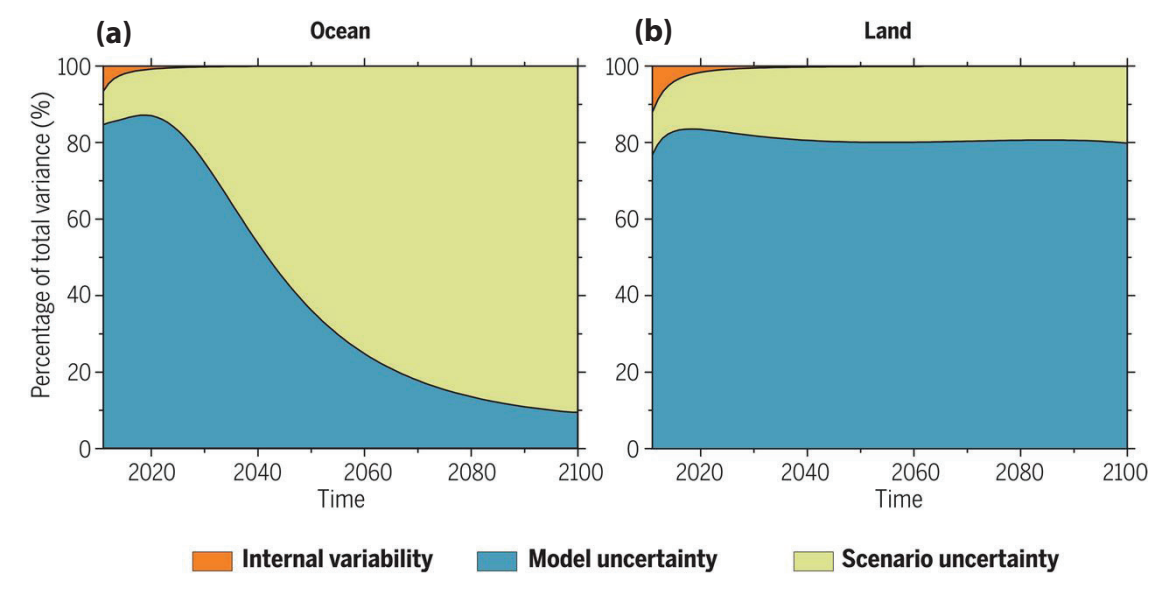

Figure 19.8. Ocean and Land Carbon Cycle Uncertainty. The percentage of total model variance or spread attributed to internal variability, model uncertainty, and scenario uncertainty in projections of cumulative global carbon uptake differs widely between **(a)** ocean and **(b)** land. The ocean carbon cycle is dominated by scenario uncertainty by the middle of the century, but uncertainty in the land carbon cycle is mostly from model structure. Data are from 12 Earth System Models using four different scenarios. [Figure source: Reprinted from Bonan and Doney 2018, used with permission from AAAS.]

cycle components) being examined must be expanded. The availability of long-term, sustained observations of environmental variables also remains key to reducing model uncertainty and thereby improving the accuracy and robustness of the model projections.

SUPPORTING EVIDENCE

KEY FINDING 1

Emissions from fossil fuel combustion in the North American energy sector are a source of carbon to the atmosphere. Projections suggest that by 2040, total North American fossil fuel emissions will range from 1,504 to 1,777 teragrams of carbon (Tg C) per year, with most coming from the United States (~80%, or 1,259 to 1,445 Tg C per year). Compared to 2015 levels, these projections represent either a 12.8% decrease or a 3% increase in absolute emissions (*high confidence*).

Description of evidence base

The projections used in this analysis are from three sources: the U.S. Department of Energy's Energy Information Administration (EIA 2017), Environment and Climate Change Canada (ECCC 2016b), and the Organisation for Economic Cooperation and Development's International Energy Agency (IEA 2016).

EIA publishes projections in *Annual Energy Outlook,* which uses the National Energy Modeling System, an integrated model that aims to capture various interactions of economic changes and energy supply, demand, and prices. Typically, reference cases are built with assumptions about known technologies; current laws, regulations, and standards; and views of economic and demographic trends that conform to leading economic forecasters and demographers. These cases are compared to a series of side cases. In the case of EIA, these side scenarios include high and low prices of oil, high and low economic growth, and whether or not the U.S. Environmental Protection Agency's Clean Power Plan (www.epa.gov/sites/production/files/2015-08/documents/cpp-final-rule.pdf) is implemented.

The ECCC model includes 1) a reference case "with current measures;" 2) actions taken by governments, consumers, and businesses up to 2013; and 3) future impacts of existing policies and measures put in place as of September 2015. The high emissions scenario uses high oil and gas prices and higher-than-average annual growth in gross domestic product (GDP). The low emissions scenario uses low world oil and gas price projections and slower GDP growth. ECCC also uses the Energy, Emissions and Economy Model for Canada (E3MC). E3MC has two components: 1) Energy 2020, which incorporates Canada's energy supply and demand structure, and 2) the in-house macroeconomic model of the Canadian economy. Modeling estimates are subject to consultations with various stakeholders (including provincial and territorial governments) to review modeling assumptions, implemented policies and measures, and emissions estimates. The modeling assumptions also undergo a periodic external review process.

IEA (2016) produced a special report on Mexico's energy outlook in light of the energy reform efforts (*Reforma Energetica*) that Mexico initiated in 2013, which brought an end to long-standing monopolies within the energy sector. According to IEA (2016), total energy demand has grown by 25% since 2000 and electricity consumption by 50%. IEA uses three scenarios for its global projections and deployed them for the Mexican study: 1) "New Policies," 2) "Current Policies," and 3) "450," which is largely aspirational. The New Policies scenario is the central case informed by an approximately 20% increase in energy demand and a growth rate averaging 0.7% per year. As

in the other scenarios, IEA decouples energy demand growth from economic growth, reflecting a structure shift in economies, a growing service sector, and energy-efficiency improvements.

Major uncertainties

Energy market projections and fossil fuel emissions futures are subject to uncertainty because many factors that shape energy decisions and future developments in technologies, demographics, and resources cannot be foreseen with certainty. These factors include economic and demographic growth, energy prices, technological innovation and adoption, government policies, laws and regulations, and international conditions. In addition, while attempts were made to standardize the sources and gases in inventories across nations, differences in greenhouse gas protocols (see Appendix E: Fossil Fuel Emissions Estimates for North America, p. 839) prevented complete consistency.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Although there is uncertainty in individual projections and in projecting trends in energy markets, all estimates agree that emissions from fossil fuel combustion in North America are a source of carbon to the atmosphere and will continue to be a source into the future.

Summary sentence or paragraph that integrates the above information

Emissions from fossil fuel combustion in the North American energy sector currently serve as a source of carbon to the atmosphere and will continue to do so into the future. Uncertainty in projections arises from the influence of policies, technologies, prices, economic growth, demand, and other difficult-to-predict variables.

KEY FINDING 2

Land, ocean, coastal, and freshwater systems are currently net sinks of carbon from the atmosphere, taking up more carbon annually than they release. However, emerging understanding suggests that the future carbon uptake capacity of these systems may decline, depending on different emissions scenarios, with some reservoirs switching from a net sink to a net source of carbon to the atmosphere (*high confidence*).

Description of evidence base

Most work examining future carbon cycle changes and potential feedbacks with climate and rising atmospheric carbon dioxide (CO_2) has been conducted at the global scale as part of coupled carbon-climate model intercomparison efforts including the Coupled Model Intercomparison Project Phase 5 (CMIP5; Friedlingstein 2015; Friedlingstein et al., 2014). As a result, published estimates of projections specific to both the land carbon sink and coastal ocean carbon uptake in North America are lacking.

To provide an estimate of future land carbon sink evolution in North America, this chapter relied on the globally gridded net biome productivity simulated by nine CMIP5 models (Ciais et al., 2013; Friedlingstein 2015). With the exception of CESM1-BGC, which was not available on the CMIP5 data download page, the models and set of simulations used here (and in Figures 19.3, p. 772, and 19.4, p. 773) are the same as those used in Ch. 6 of the *Intergovernmental Panel on Climate Change Fifth Assessment Report* (IPCC; Table 6.11): CanESM2, GFDL-ESM2G, GFDL-ESM2M, HadGEM2–ES, IPSL–CM5A-LR, MIROC-ESM, MPI–ESM–LR, NorESM1–ME,

and INMCM4. The simulation output was placed into a consistent 0.5° grid and trimmed to North America (10° to 70°N and 50° to 170°E). Projected land sink estimates were evaluated for all four of the Representative Concentration Pathways (RCPs; van Vuuren et al., 2011) used in the latest IPCC report:

1. **RCP8.5 High Emissions Scenario.** Projects increasing CO_2 and methane (CH_4) emissions over time due to increased energy intensity as a result of high population growth and lower rates of technology development leading to radiative forcing of 8.5 watts per square meter (W/m^2) by 2100. This scenario assumes an increase in cropland and grassland area driven by the demands of population growth.

2. **RCP6.0 Stabilization Scenario.** Projects a range of technologies and strategies to reduce CO_2 emissions after the year 2080, coupled with fairly steady CH_4 emissions throughout the century to stabilize radiative forcing at 6 W/m^2 in 2100. This scenario assumes an increase in cropland area, but a decline in pasture area due to aggressive implementation of intensive animal husbandry.

3. **RCP4.5 Stabilization Scenario.** Projects a range of technologies and strategies to reduce CO_2 emissions after 2040, coupled with fairly steady CH_4 emissions throughout the century to stabilize radiative forcing at 4.5 W/m^2 in 2100. This scenario assumes a decrease in cropland and grassland area due to climate policies that value carbon in natural vegetation.

4. **RCP2.6 Low Emissions Scenario.** Projects an increased use of bioenergy and carbon capture and storage, which leads to substantial reduction in CO_2 emissions after 2020. This reduction coupled with declining CH_4 emissions from energy production, transportation, and livestock leads to a peak in radiative forcing of 3 W/m^2, followed by a decline to 2.6 W/m^2 by 2100. Cropland area increases, but largely as a result of bioenergy production. Grassland area remains relatively constant as the increase in animal production is offset by more intensive animal husbandry.

For the North American coastal ocean, this report used three CMIP5 models (GFDL-ESM2M [Dunne et al., 2013], HadGEM-ESM [Martin et al., 2011], and MIROC-ESM [Watanabe et al., 2011]) to estimate a range of historical (1870 to 1995) and future carbon uptake within the exclusive economic zones (EEZs) of North America (approximately 22.5×10^6 km^2). Since 1870, North American EEZs have taken up 2.6 to 3.4 petagrams of carbon (Pg C). These regions are projected to take up an additional 10 to 12 Pg C by 2050 and another 17 to 26 Pg C in the second half of this century (2050 to 2100). Global projections of ocean carbon uptake vary depending on emissions scenarios (Ciais et al., 2013). Under lower future emissions scenarios (e.g., RCP2.6 and RCP4.5), the strength of the ocean carbon sink starts to level off toward the end of the century. For the North American Pacific Coast, the combined effect of multiple factors (e.g., increasing atmospheric CO_2, surface warming, less vertical mixing with greater vertical stratification, and increases in horizontal temperature gradients) may lead to greater and more persistent CO_2 outgassing nearshore and lower productivity offshore (see Ch. 16: Coastal Ocean and Continental Shelves, p. 649).

Major uncertainties

The balance between positive and negative influences of climate and atmospheric CO_2 on the global carbon cycle is not well constrained in models (see Figure 19.5, p. 775; Ciais et al., 2013; Graven 2016). Although models tend to agree on the direction of the carbon uptake response to both climate warming and rising CO_2, they show low agreement on the magnitude (size) of this response (Ciais et al., 2013). In land carbon cycling, many current models do not consider nutrient cycle processes or the coupling of the nitrogen and carbon cycles (Ciais et al., 2013). In addition, model response to climate warming is highly uncertain. Climate warming could lead to an increase or decrease in carbon uptake, depending on a number of factors that will vary by region and the species present within a given ecosystem (Graven 2016). Major sources of uncertainty in models are projected changes in permafrost and soil carbon storage (see Section 19.7.2, p. 780). Many models do not explicitly account for permafrost dynamics and include outdated representations of soil carbon turnover that are inconsistent with emerging scientific understanding (Bradford et al., 2016).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Land, ocean, coastal, and freshwater systems are currently net sinks of carbon from the atmosphere. Although projections vary depending on future climate and carbon emissions scenarios, it is likely that under some future climate and CO_2 emissions scenarios these systems will turn from a net sink to a net source of carbon.

Summary sentence or paragraph that integrates the above information

It is the balance between the response of land and ocean systems to future climate and rising atmospheric CO_2 that will ultimately determine the strength and extent of carbon uptake by these systems and whether they continue to be net sink of carbon from the atmosphere or switch to being a net source.

KEY FINDING 3

Human-driven changes in land cover and land use will continue to be key contributors to carbon cycle changes into the future, both globally and in North America. Globally, land-use change is projected to contribute 10 to 100 Pg C to the atmosphere by 2050 and between 19 and 205 Pg C by 2100. Conversely, in the United States, land use and land-use change activities are projected to increase carbon stocks in terrestrial ecosystems by about 4 Pg C from 2015 to 2030. This projected increase is primarily driven by the growth of existing forests and management activities that promote ecosystem carbon uptake, often in response to changes in market, policy, and climate (*high confidence*).

Description of evidence base

Global estimates are based on Brovkin et al. (2013), who examined the difference in land carbon storage between the ensemble averages of simulations with and without land-use changes using RCP2.6 and RCP8.5. The RCP2.6 scenario assumes that climate change mitigation is partially achieved by increasing the use of bioenergy crops. Under this scenario, the global land area used for pastures is more or less constant over the simulation period, and increases in production (animal-based products) are achieved through changes in approaches to animal husbandry (Brovkin et al., 2013). In the RCP8.5 scenario, food demands and increasing population drive

the expansion of croplands and pastures (and the loss of forested lands). The model ensemble includes six CMIP5 models for the projections: CanESM2, EC-Earth, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM, and MPI-ESM-LR. Across all models, Brovkin et al. (2013) found a robust signal showing a loss of global land carbon storage because of projected land-use and land-cover change activities.

There is a lack of projections of emissions and sink trends for land use, land-use change, and forestry (LULUCF) activities specific to North America as a whole. U.S. estimates are based on the *Second Biennial Report of the United States of America* (U.S. Department of State 2016). That report presents a range in carbon sequestration estimates (689 to 1,118 teragrams [Tg] of CO_2 equivalent [CO_2e] per year by 2030) associated with U.S. land-use change and forestry activities. Also estimated is that emissions from forestry and land use will be 28 Tg CO_2e in 2030.

To project cumulative carbon uptake from 2015 to 2030, the emissions estimate associated with forestry and land use (28 Tg CO_2e) is subtracted from the low and high estimates of sequestration associated with forestry and land use (689 to 1,118 Tg CO_2e). These values are then combined and divided by 2 to arrive at an average projected net uptake per year in 2030 of 875.5 Tg CO_2e per year. This value is converted to teragrams of carbon (239 Tg C per year) and multiplied by 15 to arrive at a cumulative uptake of 3.6 Pg C from 2015 to 2030.

Major uncertainties

Uncertainties arise from how land use and land-use change information is implemented into the carbon cycle representation of ecosystem models (i.e., the inclusion or exclusion of specific land-use processes such as wood harvest; Brovkin et al., 2013). In global projections, uncertainty also arises from the lack of coupled carbon-nitrogen (and phosphorus) dynamics in models. The models in this study do not account for the effect of nitrogen or phosphorus limitation on land ecosystems or CO_2 fertilization.

For both the global and North American projections, there is also uncertainty in estimates of population growth and its potential impact on forest and agricultural land area. Moreover, there is general uncertainty in the potential future magnitude and timing of land-use change impacts on the land carbon cycle because of the difficulty in projecting the outcome of complex and interacting environmental, climate, and socioeconomic systems.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Several studies generally agree with high confidence that direct human influence on land use and land-cover change is a large driver of future potential carbon cycle changes. Model projections for North America agree that U.S. LULUCF activities will continue to result in net carbon uptake (i.e., carbon sequestration) to 2030. However, uncertainty in population growth and its impact on forests and agricultural land leads to considerable uncertainty in carbon uptake projections beyond 2030 associated with land-use change and forestry activities.

Summary sentence or paragraph that integrates the above information

There is high confidence that land use, land-use change, and management play important roles in both the global and North American carbon cycles. However, the future magnitude and timing of carbon cycle changes emerging from land use and land-use change depend on a number of factors

that are difficult to project, including population growth and environmental and economic policies, all of which will drive changes in land use.

KEY FINDING 4

The enhanced carbon uptake capacity of ocean and terrestrial systems in response to rising atmospheric CO_2 will likely diminish in the future. In the ocean, warmer and more CO_2-enriched waters are expected to take up less additional CO_2. On land, forest maturation, nutrient limitations, and decreased carbon residence time in soils will likely constrain terrestrial ecosystem response to rising CO_2 (*high confidence*).

Description of evidence base

Although models tend to agree on the direction of the carbon uptake response to rising CO_2, they show low agreement on the magnitude (i.e., size) of this response, particularly for terrestrial ecosystems (see Figure 19.5, p. 775). However, some factors potentially important for limiting the CO_2 fertilization response of terrestrial ecosystems are not currently represented in models, including 1) the age distribution of forest trees, 2) nutrient limitation, and 3) soil carbon turnover rates.

Forest Age. Ecosystem CO_2 enrichment experiments in North American forests tend to show that, in the short term (e.g., up to 10 years), CO_2 fertilization increases forest production by 20% to 25% (McCarthy et al., 2010; Norby et al., 2010; Talhelm et al., 2014). However, most of these forest experiments were conducted in young forests that also were accumulating biomass under ambient CO_2 concentrations. The few experiments that have been conducted on individual trees in more mature forests tend to show little or no growth response (Bader et al., 2013; Klein et al., 2016).

Nutrient Limitation. Nutrients will likely constrain land carbon cycle response to rising CO_2 (e.g., Norby et al., 2010). Many current models do not consider nutrient cycle processes (Ciais et al., 2013; Hoffman et al., 2014), contributing substantial uncertainty to the overall accuracy of CO_2–carbon cycle feedback estimates. Even models that do consider nutrient cycling exhibit substantial uncertainty in responses of terrestrial ecosystems to increased atmospheric CO_2 (Walker et al., 2015; Zaehle and Dalmonech 2011).

Soil Carbon Turnover Rates. Results from some studies suggest that soil carbon storage may increase with rising atmospheric CO_2 (e.g., Iversen et al., 2012), even if the latter does not lead to increased carbon storage in forest biomass. However, soil carbon input may change microbial decomposition rates and the rate of soil carbon turnover, leading to less overall soil carbon storage (Hungate et al., 2013; van Groenigen et al., 2014).

In the ocean, warmer and more CO_2-enriched waters are expected to take up less additional CO_2 and be less resistant to changes in pH (Ciais et al., 2013). Several studies (Gattuso et al., 2015; Randerson et al., 2015; Bopp et al., 2013; Doney et al., 2009) have investigated in detail the impacts of contrasting emissions scenarios on ocean dynamics and marine and coastal ecosystems, including the goods and services that they provide. Alongside changes in ocean dynamics and a slowing of the ocean sink, these studies also highlight the fact that phytoplankton and zooplankton populations are likely to shift toward groups that favor higher temperature, greater physical stratification, and elevated CO_2 conditions, both in terms of trait diversity within groups

(e.g., Dutkiewicz et al., 2013) and in some groups being favored over others (e.g., slow growing, CO_2-limited nitrogen fixers; Hutchins et al., 2007).

Major uncertainties

See previous section describing the evidence base.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Models tend to agree on the direction of land and ocean carbon uptake response to rising CO_2, but they show less agreement on the magnitude of this response. However, multiple points of evidence suggest that the strength of net carbon uptake in response to rising CO_2 will decrease into the future.

Summary sentence or paragraph that integrates the above information

The recent increase in the carbon uptake capacity of ocean and terrestrial systems in response to rising atmospheric CO_2 from human-driven emissions will likely diminish in the future. Warmer and more CO_2-enriched ocean waters are expected to take up less CO_2 as climate warms due to a number of factors. Such factors, including forest maturation, nutrient limitations, and decreased carbon residence time in soils, will likely constrain terrestrial ecosystem response to rising CO_2.

KEY FINDING 5

Soil carbon losses in a warming climate will be a key determinant of the future North American carbon cycle. An important region of change will be the Arctic, where thawing permafrost and the release of previously frozen carbon will likely shift this region from a net sink to a net source of carbon to the atmosphere by the end of the century (*very high confidence*).

Description of evidence base

A meta-analysis of results from soil warming experiments indicates that soil carbon stock response to climate warming is variable but predictable and depends on the size of the soil carbon pool and the extent and duration of warming (Crowther et al., 2016). As a result, projected soil carbon losses are greatest at northern latitudes (e.g., Arctic and subarctic; see Figure 19.7, p. 777, which have large soil carbon stocks and some of the most rapid rates of projected warming (Crowther et al., 2016; see also USGCRP 2017a and Section 19.3.3, p. 770). With continued warming and large-scale losses of near-surface permafrost, almost all terrestrial carbon cycle models indicate that, by the end of this century, the Arctic could shift from a sink to a source of carbon (Cox et al., 2000; Fisher et al., 2014b).

Major uncertainties

Although there is considerable agreement that climate warming will lead to carbon loss from permafrost regions, the amplitude, timing, and form of carbon release remain topics of debate (e.g., McGuire et al., 2018; Lenton et al., 2008; Schuur et al., 2015; Slater and Lawrence 2013). This disagreement stems from a lack of understanding of three key factors that determine the potential climate feedback of the permafrost carbon pool: 1) the area and depth of permafrost vulnerable to release, 2) the speed with which carbon will be released from thawing soils, and 3) the form of carbon (e.g., CO_2 and CH_4) that will be released (Schuur et al., 2013, 2015).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

While some uncertainty remains about the timing, speed, and form of carbon release from permafrost thaw, there is strong agreement across multiple studies that climate warming will result in carbon loss from permafrost soils. Over time, under increased rates of warming in the Arctic, the carbon loss from permafrost thaw will likely cause high northern latitudes to switch from a net sink to a net source of carbon to the atmosphere.

Summary sentence or paragraph that integrates the above information

Although the amplitude, timing, and form of carbon released from thawing permafrost are still under study, there is very high confidence that warming will lead to soil carbon loss from permafrost regions.

KEY FINDING 6

Carbon storage in both terrestrial and aquatic systems is vulnerable to natural and human-driven disturbances. This vulnerability is likely to increase as disturbance regimes shift and disturbance severity increases with changing climatic conditions (*high confidence*).

Description of evidence base

Natural and human-driven disturbances will influence future vegetation carbon storage. Forest disturbance is a fundamental driver of terrestrial carbon cycle dynamics (Hicke et al., 2012). Harvesting, fire, wind throw, storms, pathogen and pest outbreaks, and drought collectively lead to the removal of 200 Tg C from U.S. forests annually (Williams et al., 2016). Initially, most disturbances shift an ecosystem to a carbon source, while recovery from disturbance is commonly associated with greater net ecosystem carbon storage (Magnani et al., 2007; Odum 1969). Hence, the effects of disturbance on carbon balance in forests are both immediate and lagged, and potentially long lasting. Given current management practices, climate change is likely to increase disturbance frequency and intensity across multiple spatial and temporal scales (Running 2008). Fire activity generally is expected to increase (Sommers et al., 2014; Westerling et al., 2006) in many regions, with fire seasons starting earlier and ending later compared to previous decades (Jolly et al., 2015). With climate warming, the range of insects (e.g., mountain pine beetle) is expected to expand into higher elevations and latitudes, putting previously unaffected forests at risk (Bentz et al., 2010; Kurz et al., 2008). Evidence suggests that the extent and severity of forest insect disturbances also are increasing with changing climate conditions (Kurz et al., 2008).

Freshwater ecosystems are particularly vulnerable to anthropogenic disturbances and are considered to be among the most threatened ecosystems on the planet (Vorosmarty et al., 2010). Human activities such as water management, river fragmentation by dams, alteration of natural flow, construction of water impoundments, and land-use changes have a major impact on freshwater ecology, biology, and carbon cycling. There is high confidence that direct human impacts—including increasing urbanization, expansion of irrigated agriculture, and growing demand for water resources—will continue to dominate the threats to most freshwater ecosystems globally over the next three decades (Settele et al., 2014).

Major uncertainties

Projections of future carbon cycle processes are highly sensitive to the ability of models to simulate external forcings. When projecting future carbon responses to natural and human-driven

disturbances, there is a great deal of uncertainty (and intrinsic difficulty) in modeling disturbance events, particularly their timing, extent, and severity (Luo et al., 2015). Also, understanding and predicting the impacts of natural and human-driven disturbances on the carbon cycle require insights into and the ability to project management decisions, human use of land and aquatic systems, and the dynamic coupling and interconnectivity between natural and human-driven activities.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

While uncertainties remain in the ability to project the exact magnitude of carbon cycle impacts due to future disturbance events, the trajectory of land and aquatic carbon storage and loss is vulnerable to both natural and human-driven disturbances. As climate conditions change and the occurrence of extreme weather events increases, the impacts of disturbances on ecosystem carbon storage is likely to increase.

Summary sentence or paragraph that integrates the above information

Natural and human-driven disturbance will influence future vegetation carbon storage. Carbon storage in terrestrial and aquatic systems is vulnerable to disturbance events, and this vulnerability is likely to increase as disturbance regimes shift and disturbance severity increases with changing climatic conditions. However, the intrinsic predictability of disturbance events and their drivers is challenging.

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Appendix A
Report Development Process

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Led by the Carbon Cycle Interagency Working Group (CCIWG), which leads the U.S. Carbon Cycle Science Program, the *Second State of the Carbon Cycle Report* (SOCCR2) was developed as a special report of the U.S. Global Change Research Program (USGCRP) Sustained Assessment process. Elaborating on information presented in SOCCR2's Preface, see p. 5, this appendix provides further details on the development background, team structure, and process of this report.

A.1 U.S. Global Change Research Program

Founded by a Presidential Initiative in 1989, USGCRP aims to build a knowledgebase that informs human responses to climate and global change through coordinated and integrated federal programs of research, education, communication, and decision support. Subsequently, the Global Change Research Act (1990) mandated USGCRP to develop and coordinate "a comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change." CCIWG was established in 1998, and the U.S. Carbon Cycle Science Program in 1999 under USGCRP auspices (see Interagency Context of U.S. Carbon Cycle Science, p. 18, in the Preface).

USGCRP Institutional Foundations. USGCRP encompasses 13 federal departments and agencies that collectively support the largest investment in climate and global change research in the world. These governmental departments and agencies maintain and develop the observational, monitoring, data management, analysis, and modeling capabilities that support U.S. responses to global change. Providing a platform for coordination of pertinent research activities across agencies, USGCRP provides congressionally mandated data and products to inform decisions. USGCRP's Strategic Plan (USGCRP 2012) and Update to the Strategic Plan 2012–2021 (USGCRP 2017a) focus on four goals: advance science, inform decisions, conduct sustained assessments, and communicate and educate. The USGCRP agencies are listed below:

- National Aeronautics and Space Administration (NASA)
- National Science Foundation (NSF)
- The Smithsonian Institution (SI)
- U.S. Agency for International Development (USAID)
- U.S. Department of Agriculture (USDA)
- U.S. Department of Commerce (DOC)
- U.S Department of Defense (DOD)
- U.S Department of Energy (DOE)
- U.S Department of Health and Human Services (HHS)
- U.S. Department of the Interior (DOI)
- U.S. Department of State (DOS)
- U.S. Department of Transportation (DOT)
- U.S. Environmental Protection Agency (EPA)

A.2 Subcommittee on Global Change Research

The Subcommittee on Global Change Research (SGCR) oversees USGCRP's activities. SGCR operates under the direction of the National Science and Technology Council's (NSTC) Committee on the Environment and is overseen by the White House Office of Science and Technology Policy. SGCR coordinates interagency activities through the USGCRP National Coordination Office (NCO) and informal interagency working groups, such as CCIWG, which led the development of SOCCR2.

A.3 Carbon Cycle Interagency Working Group

Leading the development of SOCCR2, CCIWG comprises program managers from agencies and departments with carbon cycle–related research and funding portfolios. CCIWG developed the foundation of the report process starting circa 2014 to 2015 in response to needs identified and expressed by the North American carbon cycle science community. The working group oversaw the compilation and synthesis of report contributions from all the authors, from beginning to end. The lead CCIWG agency member for SOCCR2's administrative (legal) purposes is the USDA National Institute of Food and Agriculture (NIFA). The SOCCR2 agency co-leads are all the CCIWG member departments and agencies including the U.S. Geological Survey, DOE, the National Oceanic and Atmospheric Administration (NOAA), NASA, USDA Forest Service, USDA NIFA, National Institute of Standards and Technology, EPA and NSF. Figure A.1, p. 812, and the sections that follow describe the core SOCCR2 team and the processes it has undertaken under CCIWG auspices.

A.4 SOCCR2 Federal Steering Committee

The SOCCR2 Federal Steering Committee was established in early 2015 to provide guidance and coordination to the report staff and authors. This Steering Committee comprises a subset of CCIWG members, who scheduled sessions, town halls, presentations at relevant conferences, and webinars to further engage the community of experts and the public. The Steering Committee established the scope of the SOCCR2 process and products, ensuring the inclusion of pertinent Global Change Research Act (1990) topics and a scope responsive to several documents and reports, including 1) *A U.S. Carbon Cycle Science Plan* (Michalak et al., 2011), 2) the 2012–2021 USGCRP Strategic Plan (USGCRP 2012), and 3) other documents highlighted in the SOCCR2 Prospectus. The Steering Committee developed the Prospectus between February and May 2015, and SGCR approved it in May 2015. The Federal Steering Committee also was the primary decision-making body for SOCCR2's timeline, process, procedural matters, and guidelines and approved draft versions prior to reviews by SGCR; the public; and the National Academies of Sciences, Engineering, and Medicine (2018).

A.4.1 Lead Agency, Legal Oversight, and Federal Register Notices

USDA, specifically USDA NIFA, assumed the primary responsibility for legal oversight and legal support of the assessment process, including submission of Federal Register Notices (FRNs). USDA NIFA issued the first public FRN announcing SOCCR2 on February 12, 2016, and sought submissions of 1) nominations for contributors, 2) comments on the draft Prospectus, and 3) technical input. After completion of a public review of SOCCR2's "Fourth Order Draft," USDA, on behalf of USGCRP, issued a second FRN to announce the draft report's public comment period that started November 3, 2017.

A.4.2 U.S. Carbon Cycle Science Program Office

The U.S. Carbon Cycle Science Program Office, located at the USGCRP NCO, handled assessment coordinating functions. These functions included 1) providing leadership, support, facilitation, and technical advice for the formulation of the

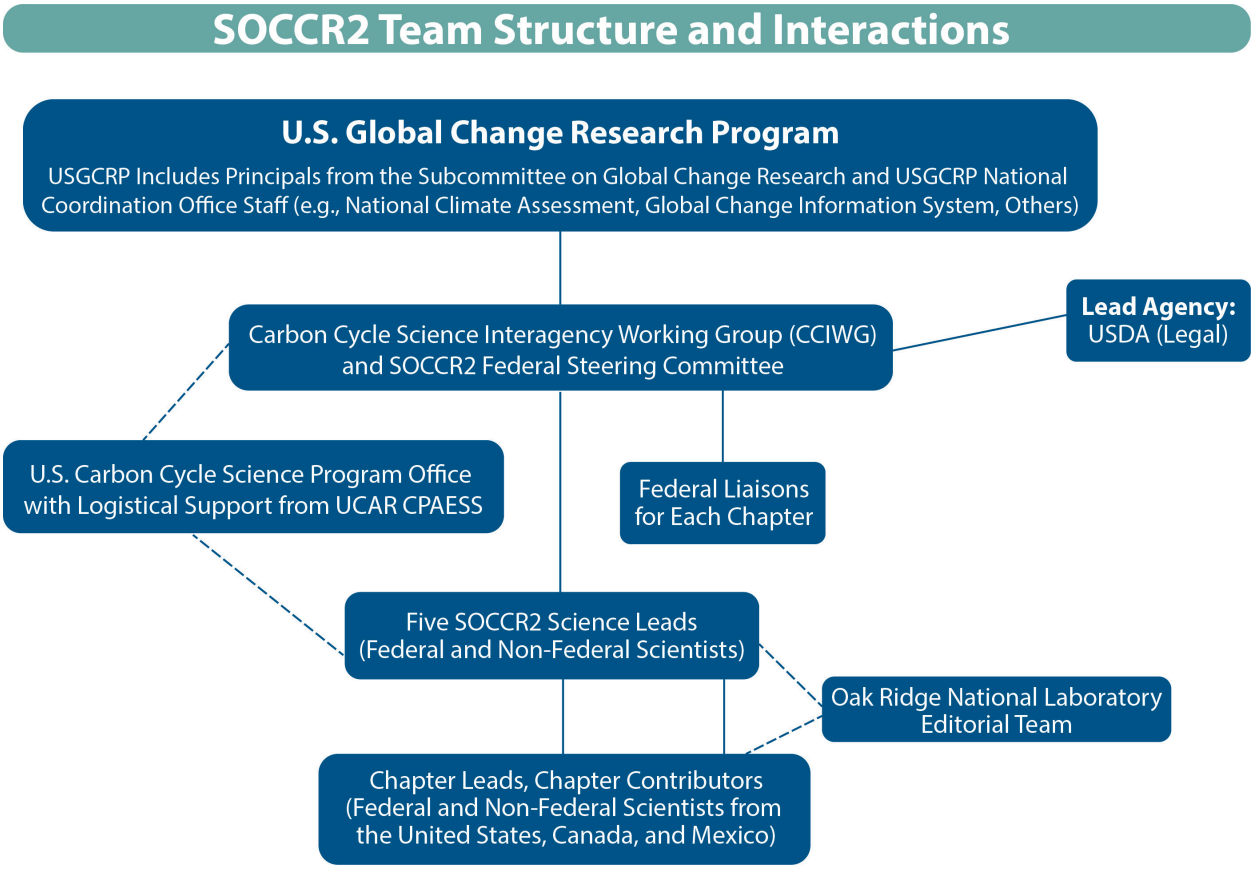

Figure A.1. The *Second State of the Carbon Cycle Report (SOCCR2)* Team Structure and Interactions. The SOCCR2 Federal Steering Committee, as a subset of the Carbon Cycle Interagency Working Group (CCIWG) under the auspices of the U.S. Global Change Research Program (USGCRP), oversaw the SOCCR2 team. The lead administrative agency was the U.S. Department of Agriculture (USDA). More than 200 governmental and non-governmental team members from the United States, Canada, and Mexico interacted iteratively during multiple drafting, reviews, revisions, and other report development processes from 2015 to 2018. [Key: UCAR CPAESS, University Corporation for Atmospheric Research's Cooperative Programs for the Advancement of Earth System Science.]

Prospectus, assessment guidelines, report content, FRNs, workshops, and engagement activities and 2) assembling federal agency experts and non-federal experts during the report development process. As needed, USGCRP staff provided technical advice, the decision tree for Information Quality, and support for reviews conducted via review.globalchange.gov. SOCCR2 workshops and other engagement activities facilitated the scoping and development of report outlines and drafts. The U.S. Carbon Cycle Science Program Office organized weekly teleconference calls for the SOCCR2 federal Steering Committee and provided the Steering Committee, CCIWG, USGCRP, and associated federal and community partners with regular progress (weekly and monthly) updates. The U.S. Carbon Cycle Science Program Office Director served as primary point of contact, liaison, and manager for SOCCR2 development, oversight, communications, and pertinent operations, as part of the SOCCR2 Federal Steering Committee and ex officio CCIWG member.

A.5 SOCCR2 Chapter Federal Liaisons

At least one member of either CCIWG or the SOCCR2 Federal Steering Committee served as a Federal Liaison for each chapter's writing team. These Federal Liaisons oversaw the development of their respective chapters in close coordination with the SOCCR2 Federal Steering Committee, regularly reporting to it on chapter progress and needs and also providing feedback to the chapter teams. Some Federal Liaisons also served as authors in their respective chapters but did not coordinate the chapter writing process. The primary responsibility for coordinating chapter authors and chapter content was that of the Chapter Lead(s), as described below. Federal Liaisons worked closely with the Chapter Leads to facilitate communication with the SOCCR2 Federal Steering Committee and CCIWG, as well as to ensure adherence to SOCCR2 guidelines provided by the SOCCR2 Steering Committee for scope, structure, and process.

A.6 Science Leads

The team of five Science Leads represented pertinent fields of carbon cycle science. The team's responsibilities included:

- Ensure balance and consistency of information across and within topics and chapters;
- Ensure emphasis on new information since the *First State of the Carbon Cycle Report* (SOCCR1; CCSP 2007);
- Ensure clear organization of the report, with a unified structure and narrative;
- Develop higher-level synthesis and overarching Key Findings, ensuring the report covers broad understanding of what is known, not known, and associated uncertainties;
- Respond to, for example, review comments on scope, emphasis, balance, and overarching Key Findings, coordinating response to specific content with chapter authors;
- Produce guidance for author teams by establishing foundational assumptions, such as for scenarios and data, and ensure that the report meets Information Quality Act requirements; and
- Organize the chapters and develop the Executive Summary and related high-level summary documentation of the report.

A.7 Chapter Teams

Within the chapter teams are Chapter Leads and Contributing Authors from the broad carbon cycle science research community. The Chapter Leads and Co-Leads (Lead authors) included a selection of federal employees and affiliates identified through existing agency collaborations and networks as well as via the February 12, 2016, FRN issued by USDA NIFA (see Section A.9, p. 814, for a description of this process). Chapter Leads and Co-Leads decided how best to organize their respective chapter teams, including division of responsibility and time requirements among Contributing Authors and Chapter Leads. The Chapter Leads and Co-Leads provided intellectual and scientific leadership for their designated chapters and were responsible for producing the chapter and addressing items of the Prospectus based on the best available scientific, technical, and socioeconomic information. They coordinated their respective chapter author team, ensuring that major sections of the chapter were completed to a high standard, were collated and delivered to the SOCCR2 Science Leads and Federal Liaisons in a timely manner, and conformed to the document's overall standards of style. They also coordinated chapter revisions with the Oak Ridge National Laboratory (ORNL) editorial team, SOCCR2 Science Leads, Federal Liaisons, and Review Editors. The ORNL editorial team provided technical support to all the SOCCR2 chapter teams. This support included formatting, text editing, graphics, design, layout, and resource site management support for graphics metadata and coordination for integration of this information with the USGCRP Global Change Information System. The editorial team also helped evaluate end-to-end content and supported

report development, identifying gaps and providing feedback and recommendations as needed.

A.8 Contributing Authors

Contributing Authors included scientists with relevant subject matter expertise nominated by Lead Authors, CCIWG or other interagency members, and the general public (through the February 12, 2016, public FRN calling for Contributing Author nominations). Where needed to fill gaps in expertise, additional subject matter experts were later invited by individual chapter teams to be Contributing Authors, based on their expertise as shown in peer-reviewed publications and other pertinent criteria.

In some instances, author teams invited special ad hoc reviews from peers (referred to as Expert Reviewers in SOCCR2) who were not authors on their chapter. Such reviews of draft chapters helped to improve the report prior to formal reviews by SGCR, the public, and the National Academies of Science, Engineering, and Medicine (NASEM). Additionally, Review Editors were involved in the process following the NASEM and public review phases, as described in Section A.9.4, p. 815.

A.9 Creating SOCCR2

A.9.1 Process for SOCCR2 and USGCRP Special Assessment Reports

Information provided in SOCCR2 updates carbon cycle science across North America and informs several chapters in USGCRP'S *Fourth National Climate Assessment* (NCA4). As described in the Preface, p. 5, a number of federally produced interagency USGCRP scientific assessment reports, including SOCCR2, are part of the USGCRP Sustained Assessment process, contributing to the robust scientific foundation of the congressionally mandated quadrennial National Climate Assessments:

1. The *Climate Science Special Report* (USGCRP 2017b), released in November 2017, is Volume I of NCA4. It provides the scientific underpinnings for NCA4 and serves as an update of the physical science presented in the *Third National Climate Assessment* (NCA3; Melillo et al., 2014).
2. The *Impacts of Climate Change on Human Health in the United States: A Scientific Assessment* (USGCRP 2016), released in April 2016, strengthens understanding of the linkages between climate change and health.
3. The NCA3, released in 2014, covered many of the same sectors and geographical regions of the United States as NCA4, providing a foundation for NCA4 sectors and regions. Additionally, NCA4 includes several new topical chapters of national and regional interest as a result of public feedback for such information.
4. The *Climate Change, Global Food Security, and the U.S. Food System* assessment (Brown et al., 2015), released in December 2015, identifies climate change impacts on global food security.

SOCCR2 followed the information quality standards, process, and review procedures for the first, second, and third formal USGCRP Sustained Assessment products above.

A.9.2 SOCCR2 Process Initiation and Author Selection

Following a January 2015 regular monthly meeting of the Carbon Cycle Interagency Working Group and discussions on the assessment development processes with the erstwhile NCA Chief of Staff, a preliminary CCIWG sub-team was assembled to start developing the SOCCR2 Prospectus. This sub-team led to the establishment of the SOCCR2 Federal Steering Committee, which would lead the organization of the first meeting with community scientists to scope SOCCR2 in May 2015, shortly after approval of the Prospectus by SGCR the same month.

The U.S. Carbon Cycle Science Program Office led the development of author guidance documents and the Prospectus for use during SOCCR2 development. These documents included 1) templates for chapters and Supporting Evidence (or Traceable Accounts)—with technical support from staff of

the USGCRP NCO and NOAA Technical Support Unit—and 2) style guides and information quality guidelines based on recent USGCRP assessments (e.g., NCA3). Authors had access throughout the process to scientific resources and writing guidance materials on a web-based platform that served as an online collaboration space and repository of SOCCR2 documents and drafts. Following the February 12, 2016, public FRN (FRN 2016) for author nominations, technical input, and comments on the SOCCR2 Prospectus, the CCIWG selected Chapter Leads for 19 chapters, also selecting more than 100 additional Contributing Authors. This writing team comprises scientists and technical experts representing U.S. agencies, national laboratories, universities, and the private sector. Later, additional Contributing Authors were invited by Chapter Leads to provide special input on select areas of the assessment. A team of five Science Leads also was selected from U.S. federal agencies, national laboratories, and academia to provide high-level scientific expertise and assistance, specifically to ensure consistency in scientific information across the report.

A.9.3 Author Training and Drafting

All 19 SOCCR2 author teams met multiple times by phone, web, and in person and produced various iterations of their chapters after beginning work in May 2016. Supporting Evidence sections (i.e., Traceable Accounts) at the end of each chapter provide transparent information about the authors' deliberations to arrive at their expert judgment regarding the level of certainty related to the Key Findings of their chapters.

Author training webinars, which were available to Chapter Leads and other interested authors, built on previously shared written guidance and included the following topics:

- Report development process and requirements
- Development of Key Findings and Supporting Evidence (i.e., Traceable Accounts accompanying each Key Finding)
- Graphics metadata requirements and the Global Change Information System

Author training webinars were recorded and archived on the SOCCR2 online drive, which was created on a free, open-access document storage, synchronization, and sharing platform that allows collaborative editing of documents. Drafts, author guidelines, and pertinent materials were also posted on that platform for access at team members' convenience throughout the report development process.

A.9.4 Review Editor Selection and Role

The SOCCR2 Federal Steering Committee selected Review Editors from a slate of candidates nominated through a public open call[1] from July 18 to August 2, 2017. For their assigned chapter(s), the Review Editors were responsible for ensuring that all substantive comments received during the public comment period and from the NASEM review were appropriately addressed, providing guidance on issues noted by reviewers and ensuring that significant scientific uncertainties were adequately reflected in the subsequent revised text. Review Editors did not provide additional comments on assigned draft chapters but instead focused on the materials derived from the public comment period and NASEM review. They also ensured that author teams considered and appropriately addressed each and every comment within the SOCCR2 scope.

A.9.5 All Author Meeting

On April 3–5, 2018, all Chapter Leads and representatives were invited to participate in a 2.5-day workshop at USDA NIFA in Washington, D.C., to finalize cross-chapter references, resolve remaining inconsistencies, and implement revisions in response to both public and NASEM reviews.

A.9.6 Review Processes

Multiple formal and internal reviews of consecutive SOCCR2 drafts have taken place (see Figure P.1,

[1] www.carboncyclescience.us/news/soccr-2-review-editors-nominations/

p. 10, in the Preface), including the following six reviews.

1. Interagency review of the "Second Order Draft" by the Subcommittee on Global Change Research (SGCR) (November 8–23, 2016).

2. Interagency review of the "Third Order Draft" by SGCR (June 23 to July 21, 2017).

3. NASEM committee review of the "Fourth Order Draft" (November 3, 2017, to March 12, 2018).

4. Public comment period for the "Fourth Order Draft" (November 3, 2017, to January 12, 2018).

5. Iterative internal reviews of multiple drafts by the Carbon Cycle Interagency Working Group, SOCCR2 Federal Steering Committee members, five Science Leads, SOCCR2 Chapter Leads, Expert Reviewers, ORNL technical editors, and federal experts from different agencies (September 2016 to July 2018). For example, prior to SGCR's review of the "Third Order Draft," several additional layers of input, reviews, and revisions (February to May 2017) were provided by 1) USDA (i.e., the administrative agency lead for SOCCR2), 2) SOCCR2 Federal Liaisons (e.g., representatives from EPA and other CCIWG agencies and departments), 3) external Expert Reviewers, 4) USGCRP leadership, and 5) SOCCR2 writing teams.

6. Following the public comment period and a formal review by NASEM experts, the writing team further revised the report, which subsequently was reviewed and approved for final publication by USGCRP member agencies as part of the interagency clearance process: Final Interagency Clearance of the "Fifth Order Draft" by SGCR (July 31 to August 20, 2018).

A.9.7 Engagement Activities

Since early 2015, the SOCCR2 Federal Steering Committee convened by phone weekly, as needed, and in person at the USGCRP NCO in Washington, D.C., as part of the regular CCIWG meetings. Regular updates were provided to SGCR. Updates on the activities and progress of SOCCR2— starting May 2015, when its development was first approved by SGCR—were posted on carboncyclescience.us. The U.S. Carbon Cycle Science Program Office provided substantive updates on the report's process and development directly to SOCCR2 Chapter Leads and Contributing Authors via emails and teleconferences. In addition, USGCRP, the North American Carbon Program (NACP), Ocean Carbon and Biogeochemistry Program (OCB), and the U.S. Carbon Cycle Science Program provided regular updates to the community via periodic newsletters and list-servs.

The first SOCCR2 scoping workshop convened with community scientists in May 2015, and the first SOCCR2 Public Forum convened at NOAA National Weather Service, College Park, in February 2016. Also conducted from 2015 to 2018 were a plethora of domestic and international in-person symposia, sessions, town halls, gatherings at meetings of professional societies (e.g., the American Geophysical Union and Ecological Society of America), and online teleconferences and webinars. These meetings involved Federal Steering Committee and other SOCCR2 team members, who solicited technical input from subject matter experts and discussed SOCCR2 processes and progress with the science community and the SOCCR2 author team. The opportunity for the public to review the SOCCR2 "Fourth Order Draft" was promoted via social media (#SOCCR2, #NCA4) and newsletters of USGCRP, NACP, and OCB, as well as the NCAnet (i.e., a "network of networks" started in 2012 to support NCAs; ncanet.usgcrp.gov). One public joint informational webinar of NACP and OCB was conducted during the SOCCR2 public comment period (November 2017 to January 2018). The SOCCR2 report dissemination includes two website versions. The SOCCR2 website 1.0, produced by the U.S. Geological Survey and launched with the public release of the final report, is a static site with downloadable PDFs of each chapter. The SOCCR2 website 2.0, to be produced by NOAA in 2019, includes an interactive interface emulating the USGCRP NCA4 capabilities, including Global Change Information System and metadata documentation.

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Appendix B
Information Quality in the Assessment

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As a "highly influential scientific assessment" (HISA),[1] the *Second State of the Carbon Cycle Report* (SOCCR2) contains cited information that meets the standards of the Information Quality Act (IQA). SOCCR2 followed federal information quality, transparency, and accessibility guidelines, undergoing peer review, public review, and final interagency review in the United States.

[1] The White House Office of Management and Budget (OMB) requirements for highly influential scientific assessments (Executive Office of the President 2004) and the OMB M05-03 Peer Review Bulletin Section III (Peer Review of Highly Influential Scientific Assessments) describe making publicly available the specific information on the peer review of influential documents disseminated by the federal government: "Even for these highly influential scientific assessments, the Bulletin leaves significant discretion to the agency formulating the peer review plan. … The use of a transparent process, coupled with the selection of qualified and independent peer reviewers, should improve the quality of governmental science while promoting public confidence in the integrity of the government's scientific products." Under the auspices of the U.S. Global Change Research Program and U.S. Department of Agriculture administrative leadership, the *Second State of the Carbon Cycle Report* followed the requirements, had significant interagency leadership and interests, and underwent multiple peer reviews, including by the public and a committee of the U.S. National Academies of Sciences, Engineering, and Medicine.

B.1 Identification of Literature Sources

The assessed content in SOCCR2 incorporates referenced materials derived primarily from the existing, peer-reviewed scientific literature and is consistent with guidance regarding the use of other literature. It adheres to the U.S. Department of Agriculture's (USDA) Information Quality Guidelines (USDA 2018) and administrative processes, as well as the Office of Management and Budget's federal information quality, transparency, and accessibility guidelines (Executive Office of the President 2004) for a HISA-appropriate document. Information from several sources was assessed, including:

1. A public request for technical input released by USDA on behalf of the U.S. Global Change Research Program (USGCRP) and the Carbon Cycle Interagency Working Group (CCIWG) on February 12, 2016 (FRN 2016);
2. Expert awareness of the literature from the authors;
3. Information provided during scoping and writing workshops and public engagement events such as professional town halls (see Appendix A: Report Development Process, p. 810); and
4. Continuous chapter-specific identification, information quality checks, and exchange of pertinent technical resources and up-to-date scientific literature by SOCCR2 team members and associated federal agencies.

The first SOCCR2 Federal Register Notice (FRN 2016) included a 30-day call for scientific information and technical input (e.g., submissions of recent, relevant, and scientific and technical research

studies including observed, modeled, and projected carbon cycle science information that has been peer-reviewed and published or accepted for publication in scientific journals and governmental reports). The Federal Register Notice included a summary of the draft Prospectus and the proposed report structure and scope, along with a web link to the detailed SOCCR2 draft Prospectus, for the public to provide pertinent input and comments via globalchange.gov. The finalized Prospectus and related SOCCR2 resources are available at www.carboncyclescience.us/state-carbon-cycle-report-soccr#Resources.

In November 2017, USDA issued a second Federal Register Notice (FRN 2017) on behalf of the USGCRP and U.S. Carbon Cycle Science Program that sought input from the public on the "Fourth Order Draft" of SOCCR2. The U.S. National Academies of Sciences, Engineering, and Medicine's (NASEM) Committee to Review the SOCCR2 Draft also published a review of the same draft in March 2018 (National Academies of Sciences, Engineering, and Medicine 2018). Additional literature and information sources were incorporated into SOCCR2 in response to both the public and NASEM reviews and to newly available scientific information.

B.2 Compliance with the Information Quality Act

The SOCCR2 Federal Steering Committee and Science Leads developed a SOCCR2 Author Guide, which contained specific guidance on maintaining information quality and adhering to the IQA. They provided the guide to the assembled author team of each chapter at the beginning of the report development process in early 2016. The guidance included a decision tree developed and provided by USGCRP, as previously used by the Climate and Health Assessment (USGCRP 2016). The decision tree and a list of provided questions guided the authors' consideration of whether and how to use source materials in SOCCR2. It assisted authors in evaluating potential sources and references from the peer-reviewed scientific literature and governmental reports and in using gray literature in limited situations, identifying needed additional documentation to justify its use. Accordingly, during each chapter's development and the revisions arising from the iterative peer and federal reviews occurring between the summers of 2016 and 2018, chapter teams assessed available literature and information sources, primarily focusing on and using peer-reviewed scientific literature (see References and Supporting Evidence at the end of each chapter). Because SOCCR2 is a special USGCRP Sustained Assessment report that also contributes to the *Fourth National Climate Assessment Vol. II* (due to be published in late 2018), many of these guidelines are consistent with or directly derived from the *Third National Climate Assessment* (Melillo et al., 2014). The guidelines, along with guidance documents from other Sustained Assessment special reports, were adapted to the specific context of the SOCCR2 effort.

B.3 Gray Literature

The author teams were asked to derive the Key Findings of their chapters primarily from peer-reviewed scientific literature that met all IQA criteria. However, in some cases, essential content for a specific topic was available from sources other than peer-reviewed literature, such as unofficial governmental publications, reports, white papers, or other documents generally referred to as gray literature. The author teams could include a limited number of supporting citations from gray literature that they deemed essential content not available in scientifically peer-reviewed journals, provided the authors could answer "yes" to all other IQA questions. In such limited situations where information was only available outside peer-reviewed scientific literature or governmental reports, author teams were required to evaluate potential sources with the following additional considerations:

- **Utility:** Is the particular source important to the topic of the chapter?
- **Transparency and traceability:** Is the source material identifiable and publicly available?

- **Objectivity:** Why and how was the source material created? Is it accurate and unbiased?
- **Information integrity and security:** Will the source material remain reasonably protected and intact over time?

As the administrative agency responsible for producing this report, the USDA National Institute of Food and Agriculture ensured that referenced information adhered to USDA Information Quality Guidelines (USDA 2018).

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Appendix C

Selected Carbon Cycle Research Observations and Measurement Programs[1]

https://doi.org/10.7930/SOCCR2.2018.AppC

C.1 Aquatic Observations

Gulf of Mexico Ecosystems and Carbon Cruise (GOMECC)

Description: The third GOMECC (GOMECC-3) performed a large-scale survey of ocean acidification trends and dynamics in the Gulf of Mexico on the National Oceanic and Atmospheric Administration's (NOAA) *Ronald H. Brown* ship. The NOAA Ocean Acidification Program has been charged with setting up an ocean acidification monitoring network to quantify the increase in near-surface water carbon dioxide (CO_2) and associated changes in inorganic carbon speciation. As part of the observing scheme, dedicated research cruises are conducted to investigate the water column properties along select transects, and pertinent surface water characteristics are evaluated along the cruise track. Coastal ocean measurements of unprecedented quality are used to improve understanding both of where ocean acidification is happening and of how ocean chemistry patterns are changing over time. GOMECC-3 is the most comprehensive ocean acidification cruise to date in this region, also including sampling in the international waters of Mexico for the first time.

Sponsoring agency: NOAA

Observation type: Cruise

Location: Gulf of Mexico

Timeline: GOMECC-3, July 18, 2017, to August 21, 2017; GOMECC-2, July 21, 2012, to August 7, 2012; GOMECC-1, July 10, 2007, to August 4, 2007

More information: www.aoml.noaa.gov/ocd/gcc/GOMECC3; www.aoml.noaa.gov/ocd/gcc/GOMECC2; and www.aoml.noaa.gov/ocd/gcc/GOMECC1

Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP)

Description: GO-SHIP collaborations bring together scientists with interests in physical oceanography, the carbon cycle, marine biogeochemistry and ecosystems, and other users and collectors of ocean interior data. The program also coordinates a network of globally sustained hydrographic sections as part of the global ocean and climate observing system, including physical oceanography, the carbon cycle, marine biogeochemistry and ecosystems. GO-SHIP provides approximately decadal resolution of the changes in inventories of heat, freshwater, carbon, oxygen, nutrients and transient tracers, covering the ocean basins from coast to coast at full depth (top to bottom). Its global measurements are of the highest accuracy required to detect these changes.

Sponsoring agencies: National Science Foundation (NSF) and NOAA

Observation type: Sustained ocean cruise observations

Location: Global ocean

Timeline: 2006 to present

More information: www.pmel.noaa.gov/co2/story/Hydrographic+Cruises and www.go-ship.org

[1] This appendix is a partial listing; some important observations may not be presented. Some content is adapted from *Our Changing Planet: The U.S. Global Change Research Program for Fiscal Year 2016* and includes information from GLOBALVIEW-CO2 (www.esrl.noaa.gov/gmd/ccgg/globalview/co2/co2_intro.html).

High-Resolution Ocean and Atmosphere pCO_2 Time-Series Measurements

Description: High-frequency autonomous CO_2 moorings monitor and improve understanding of the coastal ocean carbon balance, continent-scale carbon budgets and impacts of ocean acidification in coastal regions.

Sponsoring agency: NOAA

Observation type: Sustained ocean cruise observations

Location: Coastal and open ocean

Timeline: 2005 to present

More information: www.pmel.noaa.gov/co2/story/Coastal+Moorings and www.pmel.noaa.gov/co2/story/Open+Ocean+Moorings

Surface Ocean CO_2 Atlas Project (SOCAT)

Description: SOCAT is a synthesis activity for quality-controlled, surface ocean fCO_2 (i.e., fugacity of CO_2) observations by the international marine carbon research community, including more than 100 contributors. SOCAT data is publicly available, discoverable, and citable. SOCAT enables the quantification of the ocean carbon sink and ocean acidification and the evaluation of ocean biogeochemical models. Celebrating its 10th anniversary in 2017, SOCAT represents a milestone in biogeochemical and climate research and in informing policy.

Sponsoring agency: NOAA

Observation type: Surface ocean CO_2 synthesis

Location: International

Timeline: 2007 to present

More information: www.socat.info/ and www.pmel.noaa.gov/co2/story/SOCAT

Surface Water pCO_2 Measurements from Ships

Description: NOAA's automated measurement campaign of surface water CO_2 from 17 ships of opportunity (SOOP-CO_2) quantifies the fluxes of CO_2 on seasonal and regional scales.

Sponsoring agency: NOAA

Observation type: Sustained ocean cruise observations

Location: Global ocean

Timeline: 2005 to present

More information: www.aoml.noaa.gov/ocd/ocdweb/occ_soop.html and www.pmel.noaa.gov/co2/story/Volunteer+Observing+Ships+%28VOS%29

C.2 Terrestrial Observations

AmeriFlux Network

Description: The AmeriFlux Network, a community of sites and scientists measuring ecosystem carbon, water, and energy fluxes across the Americas, is committed to producing and sharing high-quality eddy covariance data. AmeriFlux investigators and modelers work together to generate understanding of terrestrial ecosystems in a changing world.

Sponsoring agencies: U.S. Department of Energy (DOE) and many partners

Observation type: Surface network

Location: Western Hemisphere

Timeline: 1996 to present

More information: ameriflux.lbl.gov

Detrital Input and Removal Experiment (DIRT) Network

Description: The international DIRT network was established to assess how rates and sources of plant litter inputs control the long-term stability, accumulation, and chemical nature of soil organic matter in forested ecosystems over decadal time scales. Sites span climatic and soil gradients, with sampling occurring about every 10 years.

Sponsoring agencies: NSF and others

Observation type: Distributed field campaign

Location: United States and global

Timeline: 1956 to present

More information: dirtnet.wordpress.com

Free-Air CO_2 Enrichment (FACE) Experiments

Description: FACE research technology creates a platform for multidisciplinary, ecosystem-scale research on the effects of elevated atmospheric CO_2 concentrations over extended periods of time. FACE technology is capable of providing a means by which

the environment around growing plants may be modified to realistically simulate future concentrations of atmospheric CO_2. FACE field data represent plant and ecosystem responses to concentrations of atmospheric CO_2 in a natural setting possible during the next century.

Sponsoring agencies: DOE, Smithsonian Environmental Research Center (SERC)

Observation type: Distributed field campaign

Location: United States and global

Timeline: 1994 to present

More information: science.energy.gov/~/media/ber/berac/pdf/Face_report.pdf and facedata.ornl.gov

Forest Inventory and Analysis (FIA)

Description: The FIA program provides statistically reliable quantitative estimates of forest area and ownership; species, volume, total tree growth, mortality, and removals; wood production and utilization rates; and forest carbon including soils. More than 150,000 forested sample plots are on non-federal lands. FIA measurements of forest carbon are the basis for U.S. reporting to the United Nations Framework Convention on Climate Change for the annual monitoring of carbon in the National Greenhouse Gas Inventory.

Sponsoring agency: U.S. Department of Agriculture (USDA) Forest Service

Observation type: Distributed field campaign supplemented by remote sensing

Location: United States

Timeline: 1930 to present

More information: www.fia.fs.fed.us

Greenhouse gas Reduction through Agricultural Carbon Enhancement network (GRACEnet)

Description: GRACEnet is a research program initiated to better quantify greenhouse gas (GHG) emissions from cropped and grazed soils under current management practices and to identify and further develop improved management practices that will enhance carbon sequestration in soils, decrease GHG emissions, promote sustainability, and provide a sound scientific basis for carbon credits and GHG trading programs. This program generates information needed by agroecosystem modelers, producers, program managers, and policymakers. Coordinated multilocation field studies follow standardized protocols to compare 1) net emissions of GHGs including CO_2, nitrous oxide (N_2O), and methane (CH_4); 2) carbon sequestration; 3) crop and forage yields; and 4) broad environmental benefits under different management systems. These systems typify existing production practices, maximize carbon sequestration, minimize net GHG emissions, and meet sustainable production and broad environmental benefit goals (e.g., carbon sequestration; net GHG emissions; and water, air, and soil quality). The data are accessible through a Geospatial Portal for Scientific Research (GPSR) application that is an ongoing effort of the USDA Agricultural Research Service (ARS) to increase the availability of research data to the broader scientific community. The data contained within this application represent complex relationships of data among hundreds of scientific measurements.

Sponsoring agency: USDA ARS

Observation type: Field campaign

Location: United States

Timeline: 2003 to present

More information: www.ars.usda.gov/anrds/gracenet/gracenet-home and www.data.nal.usda.gov/dataset/gracenet-greenhouse-gas-reduction-through-agricultural-carbon-enhancement-network_150

Gridded Soil Survey Geographic (gSSURGO) Database

Description: The gSSURGO database is the most detailed level of soil geographic data developed by the National Cooperative Soil Survey (NCSS) in accordance with NCSS mapping standards and at a variety of map scales. The three soil geographic databases are the Soil Survey Geographic (SSURGO) database, the State Soil Geographic (STATSGO) database, and the National Soil Geographic (NATSGO) database. These tabular data representing soil attributes are derived from properties and characteristics stored in the National Soil Information System (NASIS), such as soil organic carbon,

soil texture, bulk density, available water storage, salinity, water table depth, depth to bedrock, flooding, potential wetland soil landscapes, associated metadata, and land management.

Sponsoring agency: USDA Natural Resources Conversation Service (NRCS)

Observation type: Distributed field, remote-sensing, and air campaign

Location: United States

Timeline: ~1930 to present

More information: www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_053628

International Soil Carbon Network (ISCN)

Description: The ISCN is a self-chartered, scientific community resource devoted to the advancement of soil carbon research. The network coordinates independent soil research and monitoring efforts in the United States and internationally. ISCN members contribute to an open-access, community-driven soil carbon database.

Sponsoring agencies: USDA Forest Service, NRCS, and National Institute of Food and Agriculture; U.S. Geological Survey (USGS); and Lawrence Berkeley National Laboratory

Observation type: Distributed field campaign

Location: United States and global

Timeline: 2012 to present

More information: iscn.fluxdata.org/data/access-data

Landsat

Description: The Landsat series of satellites provides the longest temporal record (over 45 years) of moderate resolution data of the Earth's surface on a global basis. Landsat is a critical element of national and global carbon observation capability, providing foundational data covering many sectors of carbon observations and monitoring, such as forests, agriculture, soil, water, and land use. Landsat data, unique in quality, detail, coverage, and value, are routinely used in carbon cycle studies including mapping, modeling, and assessment.

Sponsoring agencies: National Aeronautics and Space Administration (NASA) and USGS

Observation type: Repeat measurements of surface reflectance by satellites

Location: Global

Timeline: 1972 to present

More information: landsat.usgs.gov

Long-Term Ecological Research (LTER) Network

Description: As the largest and longest-lived U.S. ecological network, LTER provides scientific expertise, research platforms, and long-term datasets to document and analyze environmental change, supporting a network of over 26 LTER sites encompassing diverse ecosystems including deserts, estuaries, lakes, the ocean, coral reefs, prairies, forests, alpine and Arctic tundra, urban areas, and production agriculture. The network was created to conduct research on ecological issues that can last decades and span huge geographical areas, assembling a multidisciplinary group of more than 2,000 scientists and graduate students.

Sponsoring agencies: NSF, USDA Forest Service, USDA ARS, U.S. Department of Interior (U.S. DOI) National Park Service, U.S. DOI Fish and Wildlife Service, and U.S. Environmental Protection Agency

Observation type: Distributed field campaign, airborne, and surface network

Location: Continental United States, Alaska, Antarctica, and islands in the Caribbean and the Pacific

Timeline: 1980 to present

More information: lternet.edu

Next-Generation Ecosystem Experiment (NGEE)–Arctic

Description: Initial research of NGEE-Arctic will focus on the highly dynamic landscapes of the North Slope (Barrow, Alaska), where thaw lakes, drained thaw lake basins, and ice-rich polygonal ground offer distinct land units for investigation and modeling. This project involves mechanistic studies in the field and the laboratory; modeling of critical and interrelated water, nitrogen, carbon, and energy dynamics; and characterization of important interac-

tions, from molecular to landscape scales, that drive feedbacks to the climate system.

Sponsoring agency: DOE

Observation type: Field campaign

Location: Alaska

Timeline: 2012 to 2022

More information: ngee-arctic.ornl.gov

Next-Generation Ecosystem Experiment (NGEE)–Tropics

Description: NGEE-Tropics is a combined observational and modeling project to increase scientific understanding of how tropical forest ecosystems will respond to climatic and atmospheric changes, reduce uncertainty in Earth System Model projections, and discover whether tropical forests will act as net carbon sinks throughout this century. NGEE uses coupled observations and field campaigns in tropical forest regions and has developed a process-rich tropical forest ecosystem model at a resolution better than 10 km.

Sponsoring agencies: DOE, Smithsonian Tropical Research Institute, USDA Forest Service, and NASA

Observation type: Field and aircraft campaign

Location: Puerto Rico; Manaus, Brazil; and Panama

Timeline: 2016 to 2026

More information: ngee-tropics.lbl.gov

National Ecological Observatory Network (NEON)

Description: NEON is designed to collect and provide open data that characterize and quantify complex, rapidly changing ecological processes in terrestrial and aquatic environments across the United States. The comprehensive data, spatial extent, and remote-sensing technology provided by NEON enable a large and diverse user community to tackle new questions at scales not accessible to previous generations of ecologists.

Sponsoring agency: NSF

Observation type: Distributed field campaign, airborne, and surface network

Location: United States

Timeline: 2011 to 2048

More information: www.neonscience.org

PEATcosm 1 and PEATcosm 2

Description: PEATcosm is a mesocosm experiment in which 24 bins, each 1 m^3, are filled with relatively intact, undisturbed peat. PEATcosm 1, established in 2011, evaluates the influence of a lower water table and the shrub and *Ericaceae* communities on carbon cycling. PEATcosm 2, currently under establishment, is assessing the effect of water tables and the tree community encroachment on carbon cycles.

Sponsoring agencies: USDA Forest Service and NSF

Observation type: *In situ* measurements of carbon processes

Location: Houghton, Michigan

Timeline: 2011 to 2022

More information: www.nrs.fs.fed.us/clean_air_water/local-resources/downloads/peatcosm_information.pdf

Rapid Carbon Assessment (RaCA)

Description: RaCA is designed to develop statistically reliable quantitative estimates of the amounts and distribution of carbon stocks for U.S. soils under various land covers and to the extent possible under differing agricultural management. The project also seeks to provide 1) data to support model simulations of soil carbon change related to land-use change, agricultural management, conservation practices, and climate change and 2) a scientifically and statistically defensible U.S. inventory of soil carbon stocks.

Sponsoring agency: USDA

Observation type: Distributed field campaign

Location: United States

Timeline: 2010 to present

More information: www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054164

Spruce and Peatland Responses Under Changing Environments (SPRUCE)

Description: The SPRUCE experiment, conducted in a black spruce peat bog in the U.S. Forest Service Marcell Experimental Forest in northern Minnesota, tests mechanisms controlling the vulnerability of organisms, biogeochemical processes, and ecosystems to climate change. SPRUCE is focused on the combined responses to multiple levels of warming at ambient or elevated CO_2 levels, toward improving fundamental understanding and model representation of ecosystem processes under climate change.

Sponsoring agencies: DOE and USDA Forest Service

Observation type: Field campaign

Location: Minnesota

Timeline: 2015 to 2025

More information: mnspruce.ornl.gov

Tropical Responses to Altered Climate Experiment (TRACE)

Description: The TRACE experiment, conducted in wet tropical forests in the Luquillo Experimental Forest in northeast Puerto Rico, evaluates the effects of temperature increase on soil structure, biogeochemical cycling, plant physiology, and other key ecosystem processes, with a particular focus on understanding the relationship between temperature and carbon cycling. TRACE uses infrared heat to warm soils and understory plants and small resistance heaters to warm individual leaves in the forest canopy with the ultimate goal of improving the fundamental understanding and model representation of tropical forest processes in a warmer world.

Sponsoring agencies: USDA Forest Service and DOE

Observation type: Field campaign

Location: Puerto Rico

Timeline: 2015 to 2020 (est.)

More information: www.forestwarming.org and www.fs.usda.gov/iitf

C.3 Atmospheric Observations

Arctic-Boreal Vulnerability Experiment (ABoVE)

Description: ABoVE is a large-scale investigation of the impact of environmental change on ecosystem function, ecosystem services, and its implications for social-ecological systems in Alaska and northwestern Canada. ABoVE research links field-based, process-level studies with geospatial data products derived from airborne and satellite sensors, providing a foundation for improving analysis and modeling capabilities for northern ecosystems.

Sponsoring agencies: NASA in partnership with DOE, DOI, USDA Forest Service, and the State of Alaska, as well as several Canadian federal and provincial agencies.

Observation type: Satellite and aircraft

Location: Alaska and western Canada

Timeline: September 2015 to September 2023

More information: above.nasa.gov

Atmospheric Radiation Measurement (ARM) Airborne Carbon Measurements (ACME)

Description: The Atmospheric Radiation Measurement (ARM) user facility is a multi-laboratory DOE scientific user facility with numerous national and international collaborators. ARM is a key contributor to national and international climate research efforts. Its data are currently collected from three atmospheric observatories representing the broad range of climate conditions around the world. ARM also operates three mobile facilities and additional aerial facilities and conducts specialized campaigns. Data are available from all past research campaigns and the former Tropical Western Pacific observatory.

Sponsoring agencies: DOE and NASA

Location: Southern Great Plains, North Slope of Alaska, and eastern North Atlantic, along with ARM mobile and aerial facilities. (Past research campaigns included a variety of locations.)

Timeline: 1989 to present

More information: www.arm.gov/about and www.archive.arm.gov/discovery/#v/home/s/

Atmospheric Carbon and Transport (ACT)–America

Description: ACT-America involves five 6-week airborne campaigns to quantify anomalies in atmospheric carbon. The campaign enabled and demonstrated a new generation of atmospheric inversion systems for quantifying CO_2 and CH_4 sources and sinks.

Sponsoring agencies: NASA (EVS-2) and NOAA

Observation type: Aircraft

Location: Eastern United States

Timeline: July 2016 to May 2018 (est.)

More information: act-america.larc.nasa.gov

Airborne Microwave Observatory of Subcanopy and Subsurface (AirMOSS) Experiment

Description: AirMOSS collected and used airborne radar to collect soil moisture data from nine climatic habitats in North America to estimate how much carbon the continent is taking in or releasing to the atmosphere.

Sponsoring agencies: NASA (EVS-1)

Observation type: Aircraft

Location: Continental United States and Alaska

Timeline: March 2012 to August 2016

More Information: airbornescience.jpl.nasa.gov/campaign/airmoss

Atmospheric Tomography Mission (ATom)

Description: ATom is a global-scale aircraft sampling of the atmosphere that studies the impact of air pollution on GHGs and chemically reactive gases in the atmosphere to improve the representation of these reactive gases and short-lived climate forcers in global models of atmospheric chemistry and climate. Profiles of these gases will also provide critical information for validation of satellite data, particularly in remote areas where *in situ* data are lacking. Flights occur in each of four seasons over a 4-year period.

Sponsoring agencies: NASA (EVS-2)

Observation type: Aircraft

Location: Global

Timeline: April 2015 to April 2019

More information: science.nasa.gov/missions/atom

Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE)

Description: CARVE was a 5-year mission to measure CO_2 and CH_4 fluxes from Alaska, using sensors aboard a NASA aircraft. These measurements were combined with continuous ground-based measurements to provide temporal and regional context as well as calibration for airborne measurements. Contributions of tower and aircraft observations were provided by NOAA as well as a CARVE tower near Fairbanks that took continuous measurements of CO_2 and CH_4. Flying over 4 years with varying weather patterns allowed better understanding of the sensitivity of CO_2 and CH_4 fluxes to temperature and precipitation.

Sponsoring agencies: NASA (EVS-1) and NOAA

Observation type: Aircraft and surface network

Location: Alaska

Timeline: November 2010 to November 2015

More information: science.nasa.gov/missions/carve

Global Greenhouse Gas Reference Network (GGGRN)

Description: ***NOAA GGGRN's Cooperative Air Sampling Network*** involves weekly flask sampling at 76 sites worldwide, including 23 in North America, and four ocean cruise tracks. Air samples are collected in glass flasks and shipped to a central laboratory for analysis of CO_2, CH_4, carbon monoxide (CO), molecular hydrogen (H_2), N_2O, sulfur hexafluoride (SF_6), and stable isotopes of CO_2 and CH_4, as well as of many volatile organic compounds such as ethane (C_2H_6), ethylene (C_2H_4), and propane (C_3H_8).

Sponsoring agency: NOAA

Observation type: Flask measurement network

Timeline: 1967 (at Niwot Ridge, Colorado) to present (sites continuously added)

More information: www.esrl.noaa.gov/gmd/ccgg/flask.php

Description: ***NOAA Global Monitoring Division's Observatories*** make continuous measurements of CO_2, CH_4, CO, isotopic compositions, and other carbon cycle–relevant quantities at Barrow, Alaska; Summit, Greenland; Mauna Loa, Hawai'i; American Samoa; and the South Pole.

Sponsoring agency: NOAA

Observation type: Continuous measurements

More information: www.esrl.noaa.gov/gmd/obop

Description: ***GGGRN's Aircraft program*** conducts regular profiling at 15 sites with about a 14-day measurement frequency. Flasks are analyzed for CO_2, CO, N_2O, CH_4, H_2, and SF_6, as well as isotopes of CO_2 and CH_4 and multiple halo- and hydrocarbons.

Sponsoring agency: NOAA

Observation type: Aircraft

Timeline: 1992 to present

More information: www.esrl.noaa.gov/gmd/ccgg/aircraft

Description: ***GGGRN's Tall Tower program*** makes continuous measurements of CO_2, CH_4, and CO at seven towers of varying heights up to about 400 m above ground level.

Sponsoring agency: NOAA

Observation type: Tall tower

Timeline: 1990s to present

More information: www.esrl.noaa.gov/gmd/ccgg/towers

Megacities Carbon Project

Description: The Megacities Carbon Project aims to demonstrate a scientifically robust capability to measure multiyear emission trends of CO_2, CH_4, and CO attributed to individual megacities and selected major sectors. Studies over Los Angeles and Paris, as well as planning for a study over São Paulo, are underway.

Sponsoring agencies: NASA, National Institute of Standards and Technology, and Keck Institute for Space Studies

Observation type: Surface measurement network

Location: Los Angeles and Paris

Timeline: August 2015 (completion of current network installation) to present

More information: megacities.jpl.nasa.gov/portal

Moderate Resolution Imaging Spectroradiometer (MODIS)

Description: MODIS is a key instrument aboard the satellites Terra (originally known as EOS AM-1) and Aqua (originally known as EOS PM-1). Terra MODIS and Aqua MODIS are viewing the entire Earth's surface every 1 to 2 days, acquiring data to improve understanding of global dynamics and processes occurring on the land, in the ocean, and in the lower atmosphere, such as gross primary productivity, land cover, evapotranspiration, thermal anomalies, chlorophyll concentration, sea ice, and water inundation.

Observation type: Satellite

Location: Global

Timeline: Terra, 1999 to present; Aqua, 2002 to present

More information: modis.gsfc.nasa.gov/about

Orbiting Carbon Observatory 2 (OCO-2)

Description: OCO-2 measures CO_2 from space with the precision, resolution, and coverage needed to provide a global picture of human and natural sources and sinks. These measurements are being combined with data from ground stations, aircraft, and other satellites to help answer key questions about the global carbon cycle and how it interacts with climate change.

Sponsoring agency: NASA

Observation type: Satellite, aircraft, and surface network

Location: Global

Timeline: July 2014 to July 2016

More information: oco.jpl.nasa.gov

O_2/N_2 Ratio and CO_2 Airborne Southern Ocean (ORCAS)

Description: ORCAS is an airborne field campaign to advance understanding of the physical and biological controls on air-sea exchange of oxygen (O_2) and CO_2 in the Southern Ocean,

through intensive airborne surveys of atmospheric O_2, CO_2, related gases, and ocean surface properties over biogeochemical regions adjacent to the southern tip of South America and the Antarctic Peninsula.

Sponsoring agencies: NSF and NASA

Observation type: Aircraft

Location: Puntas Arenas, Chile

Timeline: January–February 2016

More information: www.eol.ucar.edu/field_projects/orcas

Soil Moisture Active Passive (SMAP)

Description: SMAP is a satellite mission whose goal is to provide a capability for global mapping of soil moisture and the freeze/thaw state with unprecedented accuracy, resolution, and coverage. Science objectives are to 1) understand processes that link the terrestrial water, energy, and carbon cycles; 2) estimate global water and energy fluxes at the land surface; 3) quantify net carbon flux in boreal landscapes; 4) enhance weather and climate forecast skill; and 5) develop improved flood prediction and drought-monitoring capabilities. On July 7, 2015, SMAP's radar stopped transmitting, marking the end of soil moisture radar operations; however, the passive SMAP soil moisture radiometer continues to return data.

Sponsoring agency: NASA

Observation type: Satellite

Location: Global

Timeline: January 2015 to May 2018

More information: smap.jpl.nasa.gov

SMAP Validation Experiment 2016 (SMAPVEX)

Description: The SMAPVEX-16 campaign flew an L-band radar and microwave radiometer over U.S. and Canadian agricultural areas to further evaluate SMAP satellite data products. Additional flights were associated with SMAPVEX 2015.

Sponsoring agencies: NASA, USDA, Agriculture Canada, and Canadian Space Agency

Observation Type: Aircraft

Location: Iowa and Manitoba

Timeline: June–August 2016

More information: smap.jpl.nasa.gov/science/validation/fieldcampaigns/SMAPVEX16 and smap.jpl.nasa.gov/science/validation/fieldcampaigns/SMAPVEX15

Shale Oil and Natural Gas NEXUS (SONGNEX)

Description: The SONGEX campaign aims to 1) quantify emissions of trace gases, fine particles, and CH_4 from several types of oil and shale gas basins in the western United States at different stages of development and 2) study the chemical transformation of these emissions.

Sponsoring agencies: NOAA, NASA, and NSF

Observation type: Aircraft

Location: North Dakota, Wyoming, Utah, Colorado, Texas, and New Mexico

Timeline: March–May 2015

More information: www.esrl.noaa.gov/csd/projects/songnex

Twin Otter Projects Defining Oil/gas Well emissioNs (TOPDOWN)

Description: TOPDOWN aims to understand the atmospheric impact of rapidly expanding oil and gas operations in the Bakken shale play in North Dakota through downwind cross-section flights of the active field, quantifying key atmospheric trace gases (e.g., CO_2, CO, CH_4, ethane (C_2H_6), and ozone) and black carbon using airborne *in situ* sensors and complementary airborne remote-sensing instrumentation. Subsequent flights examined the Denver-Julesburg basin in northeast Colorado and the San Juan basin in New Mexico.

Sponsoring agencies: NOAA, NASA, NSF, and DOE

Observation type: Aircraft

Location: North Dakota, Colorado, and New Mexico

Timeline: May–June 2014 and April 2015

More information: www.esrl.noaa.gov/csd/groups/csd7/measurements/2014topdown

Wintertime Investigation of Transport, Emissions, and Reactivity (WINTER)

Description: WINTER evaluates the atmospheric chemical transformations and transport associated with anthropogenic emissions during winter in the mid-Atlantic region of the United States, including the Marcellus Pennsylvania shale play. Measurements will be made in large urban and industrial plumes; coal-fired power plant emissions; and distributed emissions from oil and gas extraction, agricultural or biofuel burning, and vegetation.

Sponsoring agencies: NSF and NOAA

Observation type: Aircraft

Location: Northeastern United States

Timeline: February–March 2015

More information: www.atmos.washington.edu/~thornton/field-campaigns/wintertime-investigation- transport-emissions-and-reactivity

C.4 Additional Atmospheric Observations (Listed by Institution)[2]

Atmospheric Chemistry Research Group School of Chemistry, University of Bristol, United Kingdom

Continuous measurements of CO_2 at three sites in the United Kingdom (2012 to 2015).

Center for Atmospheric and Oceanic Studies, Tohoku University, Japan

Continuous measurements of CO_2 at Syowa Station, Antarctica (1984 to present).

Centre for Environmental and Climate Research, Lund University, Sweden

Continuous measurements of CO_2 at Hyltemossa and Norunda, Sweden (2015 to present).

Centre for Isotope Research, University of Groningen, Netherlands

Continuous measurements of CO_2 at Station Lutjewad, Netherlands (2006 to present).

Climate and Environmental Physics, Physics Institute, University of Bern, Switzerland

Continuous measurements of CO_2 at Beromünster, Switzerland (2012 to present), and Jungfraujoch, Switzerland (2004 to present).

Division of Geological and Planetary Science, California Institute of Technology, United States

Continuous measurements of CO_2 at Pasadena, California (2007 to 2013), and Palos Verdes Peninsula, California (2010 to 2013).

Earth Networks, United States

Continuous measurements of CO_2 at 28 U.S. sites out of a planned 50, with data planned to be commercially available.

Energy Research Centre of the Netherlands

Continuous measurements of CO_2 at Cesar, Cabauw, Netherlands (1992 to present).

Environment and Climate Change Canada

Continuous sampling of CO_2, CO, CH_4, and other species conducted at 22 tower sites across Canada (www.canada.ca/en/environment-climate-change.html; beginning 1988–2014 to present).

European Space Agency

SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY), an imaging spectrometer, performing global measurements of trace gases in the troposphere and stratosphere (www.sciamachy.org; March 2002 to April 2012).

Finnish Meteorological Institute

Continuous measurements of CO_2 at Pallas-Sammaltunturi, Finland (2000 to present).

[2] www.esrl.noaa.gov/gmd/ccgg/globalview/co2/co2_intro.html

Harvard University, NOAA, and National Center for Atmospheric Research, United States

Continuous and flask sampling by the HIAPER Pole-to-Pole Observations (HIPPO) project on five campaign flights (2009 to 2011).

Harvard University, United States

CO_2 Budget and Regional Airborne Study (COBRA) aircraft measurements of regional to continental fluxes of CO and CO_2 over North America (2003 to 2004).

Hohenpeissenberg Meteorological Observatory, Germany

Continuous measurements of CO_2 at Gartow, Hohenpeissenberg, and Lindenberg, Germany (2015 to present).

Hungarian Meteorological Service

Continuous measurements of CO_2 at Hegyhatsal, Hungary (1994 to present).

Institut de Ciéncia i Tecnologia Ambientals, Universitat Autonoma de Barcelona, Spain

Continuous measurements of CO_2 at seven sites in Spain (2013 to present) and flask measurements at one site in Spain (2008 to 2015).

Institut für Umweltphysik, University of Heidelberg, Germany

Continuous measurements of CO_2 at Heidelberg, Germany (1996 to 2015).

Instituto de Pesquisas Energéticas e Nucleares, Brazil

Flask measurements at Arembepe, Brazil (2006 to 2010), and Farol de Mãe Luiza Lighthouse, Brazil (2010 to 2015). Aircraft flask samples at four sites in Brazil (2010 to 2012).

Izana Atmospheric Research Center, Meteorological State Agency of Spain

Continuous measurements of CO_2 at Izana, Tenerife, Canary Islands (1984 to present).

Japan Meteorological Agency

Aircraft flask measurements (2011 to 2015) and surface continuous measurements of CO_2 at three stations in Japan (1987 to present).

Laboratoire des Sciences du Climat et de l'Environnement, France

Continuous measurements of CO_2 at Amsterdam Island (2012 to present); Mace Head, Ireland (2010 to present); and Puy-de-Dôme, France (2011 to present).

Langley Research Center, NASA, United States

Continuous measurements of CO_2 via Atmospheric Vertical Observations of CO_2 in the Earth's Troposphere (AVOCET) from various campaigns, including TRACE-P, SEAC4RS, INTEX-B, INTEX-NA, DISCOVER-AQ, DC3, and ARCTAS (2001 to present).

National Center for Atmospheric Research, United States

Quasi-continuous measurements of CO_2 at five mountaintop locations in the United States: Hidden Peak, Utah; Niwot Ridge, Colorado; Roof Butte, Arizona; Fraser Experimental Forest, Colorado; and Storm Peak Laboratory, Steamboat Springs, Colorado (beginning 2005–2007 to present).

National Institute for Environmental Studies, Japan

Flask and *in situ* continuous measurements of CO_2 aboard commercial aircraft as part of the Comprehensive Observation Network for Trace gases by an Airliner (CONTRAIL) project (1993 to present).

National Institute for Environmental Studies, Japan

Observations of infrared light reflected and emitted from the Earth's surface and the atmosphere by Japan's Greenhouse gases Observing SATellite (GOSAT). Column abundances of CO_2 and CH_4 are calculated from the observational data. GOSAT flies at an altitude of approximately 666 km and completes one revolution in about 100 minutes. The satellite returns to the same point in space in three days. Its onboard observation instrument is the Thermal And Near-infrared Sensor for carbon Observation (TANSO), which consists of two subunits: the Fourier Transform Spectrometer (FTS) and the Cloud and Aerosol Imager (CAI).

National Institute of Water and Atmospheric Research, New Zealand

Continuous measurements of CO_2 at Baring Head Station, New Zealand (1972 to present).

National Science Foundation, United States

Stratosphere-Troposphere Analyses of Regional Transport (START08) aircraft measurement campaign departing from Colorado (April–June 2008). Co-sponsors include the National Center for Atmospheric Research, University of Colorado, Harvard University, University of Miami, Princeton University, NOAA Earth System Research Laboratory, Texas A&M University, and The Pennsylvania State University.

NOAA Chemical Sciences Division, United States

Campaign-mode continuous measurements of CO_2 by a number of projects including the Aerosol, Radiation, and Cloud Processes affecting Arctic Climate (ARCPAC, 2008), California Nexus (CalNex, 2010), Southeast Nexus (SENex, 2013), Shale Oil and Natural Gas Nexus (SONGNex, 2015), and the Texas Air Quality Study (TexAQS, 2006).

Norwegian Institute for Air Research

Continuous measurements of CO_2 at Birkenes Observatory, Norway (2015 to present); Ny-Ålesund and Svalbard, Norway; and Sweden (2015 to present).

Oceans & Atmosphere Flagship – GASLAB, Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia

Flask sampling for multiple trace gas species at 15 sites worldwide, including three in North America: Alert, Canada; Mauna Loa, Hawai'i; and Estevan Point, British Columbia (early 1990s to present).

Oregon State University, United States

Continuous measurements of CO_2 at seven sites in Oregon (most beginning in 2007 to present).

The Pennsylvania State University and NOAA Global Monitoring Division, United States

Continuous monitoring of CO_2, CH_4, and CO by the Indianapolis Flux Experiment (INFLUX) at seven tower sites around Indianapolis, Indiana (2011 to 2012).

The Pennsylvania State University, United States

Measurements of CO_2, CH_4, and CO at 18 various U.S. tower and surface sites conducted intermittently for periods of up to 3 years (2007 to present).

Ricerca sul Sistema Energetico, Italy

Continuous measurements of CO_2 at Plateau Rosa Station, Italy (2008 to present).

Schauinsland Station, Umweltbundesamt (UBA, German Environment Agency)

Continuous measurements of CO_2 at Schauinsland, Baden-Wuerttemberg, Germany (2014 to present).

Scripps Institution of Oceanography (SIO), United States

Flask sampling by SIO at 16 locations worldwide including seven in North America: Alert, Nunavut, Canada; Baja California Sur, Mexico; Barrow, Alaska; Cold Bay, Alaska; Cape Kumukahi, Hawai'i; La Jolla, California; and Mauna Loa, Hawai'i (beginning 1957–1996, most continuing to present).

South African Weather Service

Continuous measurements of CO_2 at Cape Point, South Africa (1993 to present).

Swiss Federal Laboratories for Materials Science and Technology

Continuous measurements of CO_2 at Jungfraujoch, Switzerland (2009 to present).

University of East Anglia, United Kingdom

Continuous measurements of CO_2 at Weybourne, United Kingdom (2007 to present).

University of Helsinki, Finland

Continuous measurements of CO_2 at Hyytiala, Finland (2012 to present).

University of Minnesota, United States

Continuous measurements of CO_2 at Rosemount Research and Outreach Center, Minnesota (2007 to present).

University of Science and Technology, Poland

Continuous measurements of CO_2 at Kasprowy Wierch, High Tatra, Poland (1996 to present).

Utah Atmospheric Trace Gas & Air Quality Lab, University of Utah, United States

Continuous measurements of CO_2 at six sites in Utah (available from 2001 to present).

Appendix D

Carbon Measurement Approaches and Accounting Frameworks

Authors

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D.1 Approaches to Measuring Carbon Stocks and Flows

Since publication of the *First State of the Carbon Cycle Report* (SOCCR1), coordinated research supported and facilitated by multiple agencies in the United States, Canada, and Mexico has enabled significant innovative observational, analytical, and modeling capabilities and approaches to further advance understanding of the North American carbon cycle. This appendix describes such approaches and methods for carbon stock and flow estimations, measurements, and accounting.[1]

[1] This appendix describes carbon accounting and measurement approaches used in the research assessed in this report. These approaches were introduced in the Preface section titled "Methods for Estimating Carbon Stocks and Fluxes," p. 15, and are elaborated on here.

D.2 Methods for Estimating Carbon Stocks and Fluxes

D.2.1 Inventory Measurements or "Bottom-Up" Methods

Measurements of carbon contained in biomass, soils, and water, as well as ecosystem measurements of carbon dioxide (CO_2) and methane (CH_4) exchanges between land and water ecosystems and the atmosphere, constitute carbon inventories and are sometimes referred to as bottom-up approaches. Generally, carbon stocks in land ecosystems are measured with remote sensing and field sampling, which may be repeated over time to estimate changes in stocks. In addition, the exchange of CO_2 and CH_4 between land and water ecosystems and the atmosphere may be observed directly by using gas concentration measurements, directly measuring fluxes or estimating fluxes from assessments of energy consumption and sales (in the case of fossil fuel flux). Measurements in specific environments, such as urban areas, often combine demographic and activity data (e.g., population and building floor areas) with "emissions factors" that estimate the amount of CO_2 released per unit of activity. Emissions of CO_2 and CH_4 released from large sources (e.g., power plants) may be observed directly.

D.2.2 Atmospheric Measurements or "Top-Down" Methods

Observations of atmospheric concentrations of CO_2 and CH_4 are obtained using air sampling instruments on the ground, towers, buildings, balloons, and aircraft or remote sensors on satellites. Top-down approaches infer fluxes from the terrestrial land surface and ocean by coupling these atmospheric gas measurements with carbon isotope methods, tracer techniques, and simulations of how these gases move in the atmosphere. The network

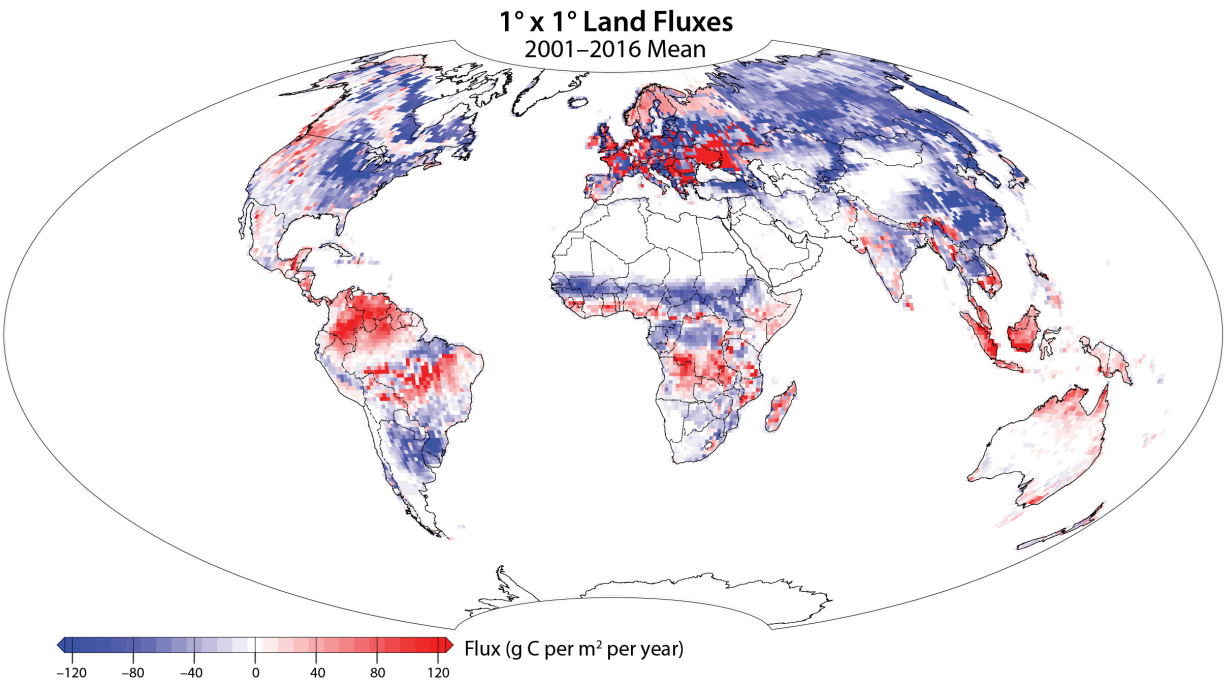

Figure D.1. Carbon Emissions as Estimated Using a Production-Based Approach. This approach assigns emissions to the place where fluxes between the atmosphere and terrestrial or aquatic ecosystems physically occur. One-degree fluxes are shown at bottom left. The map shows the land biosphere pattern of net ecosystem exchange of carbon dioxide averaged over the time period indicated, as estimated by CarbonTracker. [Figure source: Reprinted from National Oceanic and Atmospheric Administration's CarbonTracker, version CT2016 (Peters et al., 2007).]

of greenhouse gas (GHG) measurements, types of measurement techniques, and diversity of gases measured has grown exponentially since SOCCR1, providing improved estimates of CO_2 and CH_4 and increased temporal resolution at regional to local scales across North America.

D.2.3 Ecosystem Models

Terrestrial and marine ecosystem models are used to estimate quantities or fluxes of carbon that may be difficult or impossible to measure directly over large areas. The models typically are evaluated and calibrated using measurements at a limited number of sites representing different ecosystems. The models are then used to apply these measurements to larger areas or regions based on knowledge of ecosystem characteristics such as species composition, soils, weather, physiography, or management history. Ecosystem models also are used with top-down atmospheric measurements to attribute GHG observations to specific terrestrial or ocean domains of interest.

D.3 Frameworks for Carbon Accounting

Two approaches to quantify carbon cycle components inform research and analysis for scientific studies as well as for management and decisions: 1) production-based or in-boundary accounting and 2) consumption-based accounting.

Production-based, or in-boundary accounting, considers CO_2 and CH_4 flows into and out of specific areas of land or water. For a hectare of land, net emissions result from, for example, photosynthesis, CO_2 absorption by concrete, fossil fuel combustion at a power plant, and the decay of plants and animals on that parcel (see Figure D.1, this page). In practice, analyses of terrestrial ecosystems such as

forests and grasslands also typically include lateral transfers of carbon among parcels (e.g., via erosion or streamflow).

Consumption-based accounting assigns carbon flows associated with products and services (e.g., timber, electricity, food, chairs, televisions, and heat) to the places where people ultimately use those products (see Figure D.2, p. 837). This approach captures demand and trade as drivers of carbon emissions. For example, emissions from fossil fuel combustion during the production of electricity are assigned not to a power plant, but rather to the places where people use that electricity. In other examples, emissions from crop production are assigned to the place where the crop is consumed (by humans or animals), and carbon captured in trees harvested for timber is assigned to the timber mill or to the place where the timber is used. Quantification of these indirect fluxes typically employs a life cycle assessment framework that also can quantify the carbon stock residing in infrastructure and materials. Consumption-based approaches are more suited to revealing opportunities for replacing highly inefficient processes on the demand side with carbon-conserving processes (e.g., reducing GHG emissions by reducing food loss and waste), and to pointing out sectors in which demand for high-carbon products is strong (e.g., buildings that use excessive electricity compared to similarly sized buildings).

The difference between these two carbon accounting approaches is central to understanding stakeholder interests and deciding which accounting approaches to apply in different circumstances. How does responsibility for emissions divide, for example, between the person who finances a power plant that relies on fossil fuels and the people who own computers manufactured using electricity from that plant? How does responsibility for CH_4 production by cattle divide among the people who own goods made of leather, people who transport cattle to the slaughterhouse, people who own feedlots, organizations that sell hamburgers, and people who consume beef? Questions like these, often unstated, determine which carbon accounting framework is most useful for informing debate, management, and decisions.

In some sectors, and at regional or national scales, production-based and consumption-based carbon accounting yield dramatically different results. In urban ecosystems, for example, where energy and goods are imported from sometimes distant suppliers into the urban domain, consumption-based estimates can yield a very different emissions responsibility than production-based estimates. Trade among nations also leads to dramatic differences in carbon flux estimates between production- and consumption-based approaches, with carbon-intensive production dominating some economies and consumption of those goods occurring primarily on other continents. At the scale of the whole planet, the two approaches necessarily converge.

Production- and consumption-based approaches reflect supply and demand perspectives, respectively, both of which inform management and policy decisions. For example, production-based approaches illuminate the consequences of different land-use patterns and the geographic areas where inefficient production systems offer compelling opportunities for improved carbon management. They also provide information about the relative importance of different processes to trends in carbon stocks; for example, they illustrate the magnitude of CO_2 production from fossil fuel combustion in relation to CH_4 production from ruminants and carbon capture by forests. Estimates from this accounting approach also correspond to direct measurements of CO_2 and CH_4 flows into and out of terrestrial and aquatic ecosystems (e.g., with flux towers).

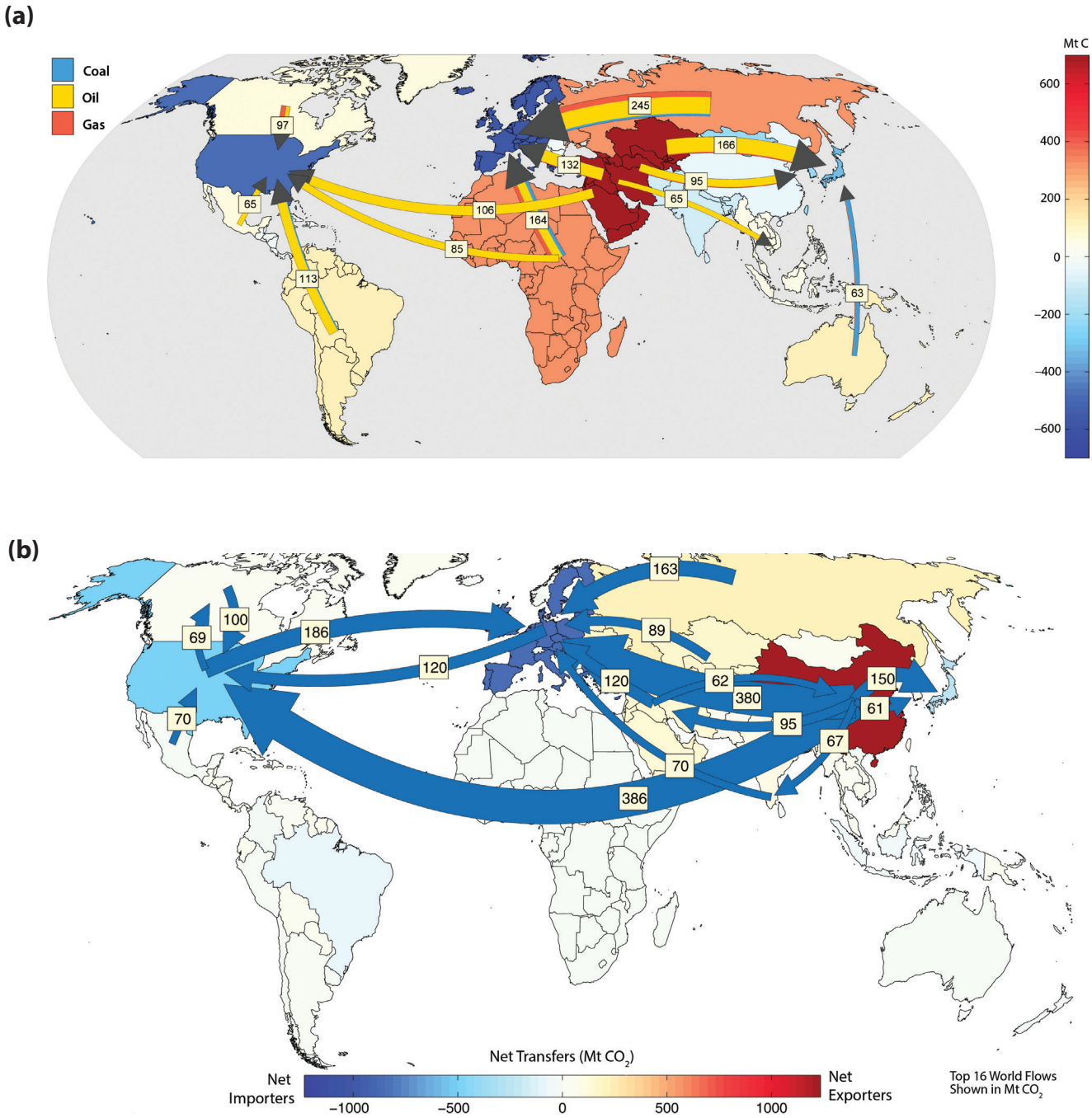

Figure D.2. Carbon Emissions as Estimated Using a Consumption-Based Approach. This approach assigns emissions to the place where goods and energy are consumed. **(a)** The top 12 inter-regional flows of fossil fuel carbon embodied in trade from extracting region to producing region, broken down by primary fuel type and disaggregated further to highlight key countries. **(b)** Fossil fuel carbon flows from extraction to consumption. [Figure sources: Panel (a) reprinted from Peters et al., 2012, used with permission under a Creative Commons Attribution License (CC BY 3.0 US). Panel (b) reprinted from Le Quéré et al., 2018, used with permission under a Creative Commons Attribution License (CC BY 4.0 US).]

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Appendix E

Fossil Fuel Emissions Estimates for North America

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E.1 Introduction

Anthropogenic carbon dioxide (CO_2) emissions from fossil fuel sources, while dominated by direct combustion for heating and energy production, can be defined to include a diverse set of industrial and agricultural processes. These include CO_2 production from cement manufacturing, gas and oil flaring, fugitive emissions, nonfuel oxidation of hydrocarbons, solid waste combustion, soil emissions, and geothermal power production. There are two general classes of global inventories: 1) those defined geographically at the nation-state scale and 2) those that generate estimates at the regular grid-cell scale (e.g., 10 km, 1 degree). The latter often are derived from the former via downscaling techniques but also may use "bottom-up" data such as emissions estimates and coordinates for power plants or airports. The available (nation-state or gridded) inventories, detailed in this appendix, cover these sectors in differing ways that cannot be reconciled directly to a common basis. In addition to their varying sectoral coverage, methodological differences among the inventories can lead to additional sources of difference (Macknick 2014). Some of the inventories are based on fuel sales, and others on activities such as number of road miles driven. The *First State of the Carbon Cycle Report* (SOCCR1) "Part II Overview" chapter (Marland et al., 2007) provides a relevant discussion of different products and methodologies.

The varying sectoral definitions, resolutions, and methodological differences make direct comparisons challenging. For example, it is sometimes unclear whether country totals from different products include fuel usage for international marine and air transport (bunker fuels). However, the difficulties reconciling the definitions used by different products can be informative of practical uncertainty when used within atmospheric inversions or budget studies.

E.2 Emissions Estimates Considered

1. **U.S. Department of Energy Carbon Dioxide Information Analysis Center (CDIAC) Version 2017 (Boden et al., 2017) for 1751 to 2014**. Emissions included in this database are those due to fossil fuel consumption (e.g., oil, coal, and natural gas), gas flaring, and cement production. Emissions are listed by country and fuel type; bunker fuels are available separately but not included in the country totals.

2. **U.S. Energy Information Administration (EIA 2017) for 1980 to 2015.** CO_2 emissions from the consumption of energy, including emissions resulting from the consumption of petroleum, natural gas, and coal, as well as from natural gas flaring. Emissions are computed from consumption statistics for each fuel type

by applying emissions factors. Data include nonfuel use of petroleum such as asphalt for street paving and exclude emissions from geothermal power generation, cement production and other industrial processes, or municipal solid waste combustion.

3. **Fossil Fuel Data Assimilation System (FFDAS) Version 2 (Rayner et al., 2010; Asefi-Najafabady et al., 2014) for 1997 to 2012.** Emissions other than power production (which use a pointwise bottom-up dataset) are estimated using data assimilation to constrain a modified Kaya identity model. The two observed fields are space-based nightlights and population density. Country totals are then created by aggregating gridded emissions using Lloyd et al. (2016, 2017) gridded country boundaries based on the Database of Global Administrative Areas, called GADM. Version 2 of FFDAS produces estimates for electricity-production, industrial, residential, commercial, and transportation (other than domestic aviation and domestic waterborne) sectors and includes a posterior uncertainty as produced by the assimilation system and prior uncertainty estimates. These map closely to the Intergovernmental Panel on Climate Change (IPCC) 1A fuel consumption category (excepting 1A3a, civil aviation, and 1A3d, navigation).

4. **Emissions Database for Global Atmospheric Research (EDGAR) Version 4.3.2 (Janssens-Maenhout et al., 2017a) for 1970 to 2012.** Total used of all emissions listed in "CO2_excl_short-cycle_org_C" from version 4.3.2, which includes IPCC categories (see Table E.1, this page, for a partial list).

5. **Emissions Database for Global Atmospheric Research Fast Track (EDGAR FT) EDGAR Version 4.3.2 FT2016 (Janssens-Maenhout et al., 2017b; Olivier et al., 2017) for 1970 to 2016.** Sectoral coverage is described as "Transport, Other Industrial Combustion, Buildings, Noncombustion, Power Industry." For unknown reasons, EDGAR FT and the standard EDGAR emissions do not agree during their common years (i.e., 2012 and before).

Table E.1. Intergovernmental Panel on Climate Change (IPCC) Source/Sink Codes and Categories

Code	Category
1A1a	Public electricity and heat production
1A1bc	Other energy industries
1A2	Manufacturing industries and construction
1A3a	Domestic aviation
1A3b	Road transportation
1A3c	Rail transportation
1A3d	Inland navigation
1A3e	Other transportation
1A4	Residential and other sectors
1B1	Fugitive emissions from solid fuels
1B2	Fugitive emissions from oil and natural gas
2A1	Cement production
2A2	Lime production
2A3	Limestone and dolomite use
2A4	Soda ash production and use
2A7	Production of other minerals
2B	Production of chemicals
2C	Production of metals
2G	Nonenergy use of lubricants/waxes (carbon dioxide)
3A	Solvent and other product use: paint
3B	Solvent and other product use: degrease
3C	Solvent and other product use: chemicals
3D	Solvent and other product use: other
4D4	Other direct soil emissions
6C	Waste incineration
7A	Fossil fuel fires

Table E.2. North American Fossil Fuel Carbon Dioxide Emissions[a]

Year	Canada	United States	Mexico	North America
2004	150.6	1569.7	120.3	1840.6
2005	152.0	1578.9	127.2	1858.1
2006	148.3	1553.7	130.7	1832.7
2007	151.2	1578.7	131.0	1860.9
2008	153.0	1531.0	134.5	1818.5
2009	146.4	1435.4	129.8	1711.5
2010	145.8	1471.4	126.6	1743.8
2011	146.5	1442.5	132.1	1721.1
2012	141.1	1396.1	135.3	1672.5
2013	141.0	1406.9	133.7	1681.7

Notes

a) Fossil fuel emissions in teragrams of carbon (Tg C) per year from the Carbon Dioxide Information Analysis Center (Boden et al., 2017; see Section E.2, p. 839).

Table E.3. Summary Statistics on North American Fossil Fuel Carbon Dioxide Emissions[a]

Quantity	Canada	United States	Mexico	North America
2004–2013 CDIAC[b] mean	147.6	1496.4	130.1	1774.1
CDIAC interannual variability (standard error of mean)	1.3	23.3	1.4	23.8
Time mean (2004–2013) of the range of the five emissions inventories in Section E.2 divided by CDIAC (percent)	30.0	5.8	14.9	5.5

Notes

a) Emissions measured in teragrams of carbon (Tg C) per year.

b) CDIAC, Carbon Dioxide Information Analysis Center.

E.3 Time Series of North American Emissions, 2004 to 2013

The CDIAC time series was chosen to represent fossil fuel emissions from Canada, the United States, and Mexico from 2004 to 2013. In part, this is due to CDIAC's long historical coverage for all three countries and its clear definition of what goes into the country totals (e.g., Marland et al., 2007). Assigning an uncertainty to the CDIAC time series is a challenge. Andres et al. (2014) discuss various ways to characterize the uncertainty of the CDIAC product and suggest that a time-average uncertainty for the United States could be about 4% (2 standard deviations). SOCCR1 (Marland et al., 2007; p. 59) suggests ±5% for developed countries, concordant with International Energy Agency (IEA 2005; Marland et al., 2007) intercomparisons for developed countries (also 5%). Here, the fractional range of the five inventories listed previously is used, averaged over time, to represent the uncertainty. Note that some of these differences are driven by categorical differences in what is included, or not included, in the global inventories. The CDIAC time series is recognized as different from the mean of the five inventories. Results are shown in Table E.2 and Table E.3, this page, and Figure E.1, p. 842.

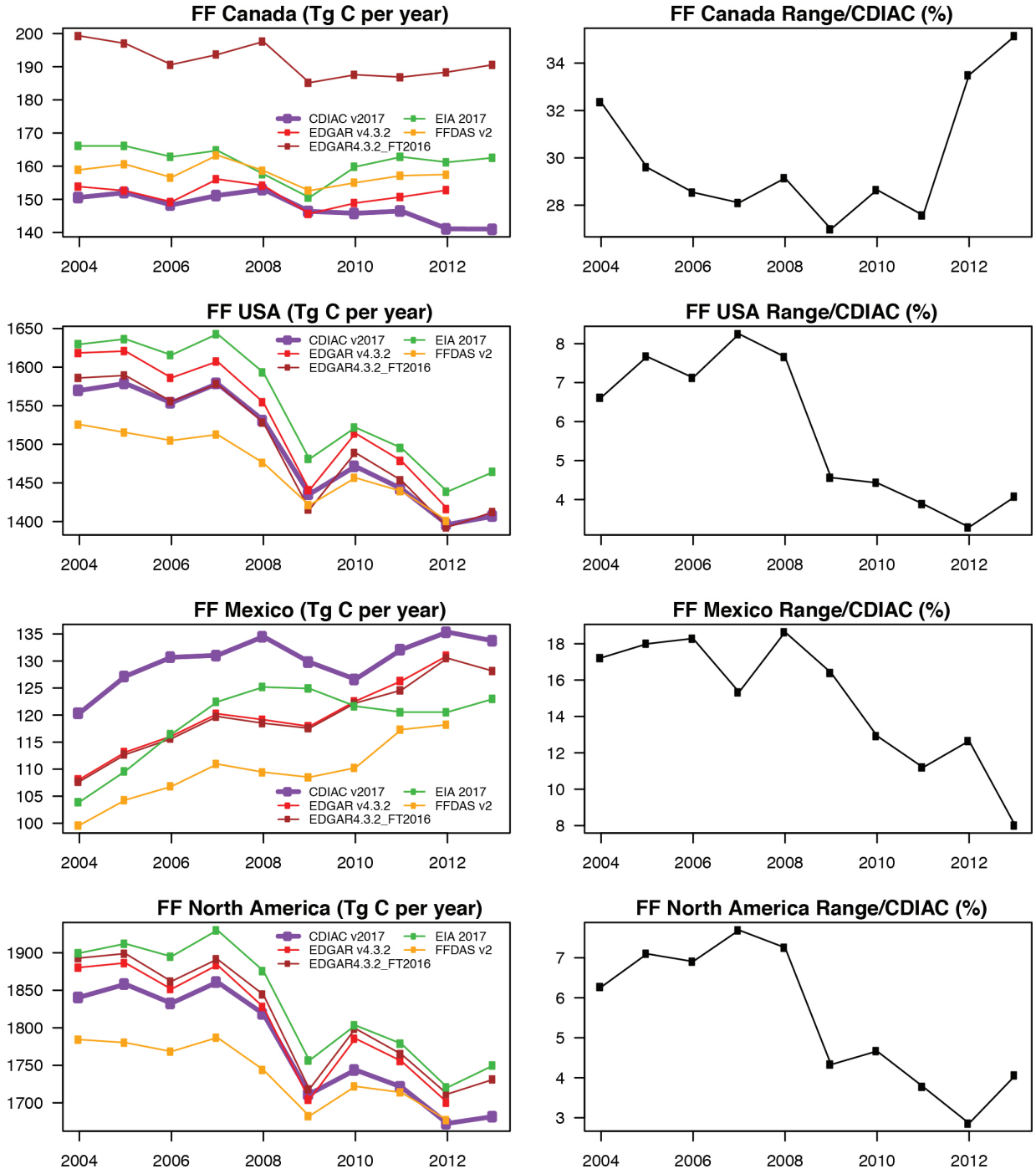

Figure E.1. Fossil Fuel Carbon Dioxide Emissions. (Left column) Data are from Canada, the United States, Mexico, and their total for North America, plotted between 2004 and 2013. **(Right column)** Graphs show the range of the estimates expressed as a percentage of the Carbon Dioxide Information Analysis Center (CDIAC) estimate for each year. Key: FF, fossil fuels; Tg C, teragrams of carbon; USA, United States (conterminous); EDGAR FT, Emissions Database for Global Atmospheric Research Fast Track; EIA, U.S. Energy Information Administration; FFDAS, Fossil Fuel Data Assimilation System.

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Appendix F
Acronyms, Abbreviations, and Units

https://doi.org/10.7930/SOCCR2.2018.AppF

Acronyms (partial list)

AAFC	Agriculture and Agri-Food Canada
ACEP	Agricultural Conservation Easement Program
ACT-America	Atmospheric Carbon and Transfer–America program
AFOLU	agriculture, forestry, and other land use
AIM	atmospheric inverse modeling
ALOHA	A Long-Term Oligotrophic Habitat Assessment
ALT	active layer thickness
ALU	agriculture and land use
ARCTAS	Arctic Research of the Composition of the Troposphere from Aircraft and Satellites
ARPA-E	Advanced Research Projects Agency–Energy (DOE)
ARRA	American Recovery and Reinvestment Act
ARS	Agricultural Research Service (USDA)
ATom	Atmospheric Tomography Mission
BATS	Bermuda Atlantic Time-series Study
BCS	Beaufort and Chukchi Seas
BECCS	bioenergy carbon capture and storage
BS	Bering Sea
C4MIP	Coupled Climate–Carbon Cycle Model Intercomparison Project
CAA	Canadian Arctic Archipelago
CAA	U.S. Clean Air Act
CAFC	Company Average Fuel Consumption
CAFE	corporate average fuel economy
CAIT	Climate Access Indicators Tool
CalNex	California Research at the Nexus of Air Quality and Climate Change
CAM	crassulacean acid metabolism
CAMS	Copernicus Atmospheric Monitoring Service
CanSIS	Canadian Soil Information Service
CARAFE	CARbon Atmospheric Flux Experiment
CARVE	Carbon in Arctic Reservoirs Vulnerability Experiment
CCAFS-MOT	Climate Change, Agriculture, and Food Security–Mitigation Options Tool
CCGT	combined-cycle gas turbine
CCIWG	Carbon Cycle Interagency Working Group (USGCRP)

CCS	carbon capture and storage
CCSC	Central California Current System
CCSN	Northern California Current System
CCSS	Southern California Current System
CDIAC	Carbon Dioxide Information Analysis Center
CDU	carbon dioxide utilization
CEC	Commission for Environmental Cooperation
CEMAC	Clean Energy Manufacturing Analysis Center
CFC	chlorofluorocarbons
CFE	community forest enterprise
CMIP	Coupled Model Intercomparison Project
CONUS	conterminous United States
CP	certificate of possession
CPP	U.S. Clean Power Plan
CRP	Conservation Reserve Program
CSKT	Confederated Salish and Kootenai Tribes
CSSR	*Climate Science Special Report*
DIC	dissolved inorganic carbon
DISCOVER-AQ	Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality
DOC	U.S. Department of Commerce
DOC	dissolved organic carbon
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
DOM	dissolved organic matter
DOS	U.S. Department of State
DOT	U.S. Department of Transportation
E10	10% blended ethanol
E3MC	Energy, Emissions and Economy Model for Canada
ECBM	enhanced coal bed methane recovery
EDCM	Erosion-Deposition-Carbon-Model
EERE	Energy Efficiency and Renewable Energy (DOE)
EEZ	Exclusive Economic Zone
EIA	U.S. Energy Information Administration
EISA	Energy Independence and Security Act
ENSO	El Niño-Southern Oscillation
EOR	enhanced oil recovery
EPA	U.S. Environmental Protection Agency
ESM	Earth System Model
ESRL	Earth System Research Laboratory (NOAA)

EU	European Union
ExACT	Ex-Ante Carbon-balance Tool
FACE	Free-Air CO_2 Enrichment
FAO	Food and Agriculture Organization
FFC	fossil fuel consumption
FIA	Forest Inventory and Analysis
FLFL	forestland remaining forestland
FOLU	forestry and other land use
FTS	Fourier Transform Spectrometer
FVS	Forest Vegetation Simulator
GAK	Gulf of Alaska
GCP	Global Carbon Project
GCRA	Global Change Research Act
GDP	gross domestic product
GEMS	General Ensemble Biogeochemical Modeling System
GeoCARB	Geostationary Carbon Cycle Observatory
GHG	greenhouse gas
GIS	geographic information system
GMx	Gulf of Mexico
GOM	Gulf of Maine
GOSAT	Greenhouse Gases Observing Satellite
GPP	gross primary production
GRACEnet	Greenhouse gas Reduction through Agricultural Carbon Enhancement network
GStL	Gulf of St. Lawrence and Grand Banks
GWP	global warming potential
HB	Hudson Bay
HIAPER	High-Performance Instrumented Airborne Platform for Environmental Research
HIPPO	HIAPER Pole-to-Pole Observations
IAGOS	In-service Aircraft for a Global Observing System
IAM	integrated assessment model
IASI	Infrared Atmospheric Sounding Interferometer
IEA	International Energy Agency
ILAMB	International Land Model Benchmarking
INFLUX	Indianapolis Flux Experiment
INGAA	Interstate Natural Gas Association of America
IPCC	Intergovernmental Panel on Climate Change
IPCC AR5	Fifth Assessment Report of the IPCC; also WG1, WG2, WG3 – Working Groups 1–3
IQA	Information Quality Act
ITC	Investment Tax Credit
LCOE	levelized cost of energy
LECZ	low-elevation coastal zone

LEED	Leadership in Energy and Environmental Design
LIDAR	light detection and ranging
LS	Labrador Shelf
LULC	land use and land cover
LULUCF	land use, land-use change, and forestry
MAB	Mid-Atlantic Bight
MCI	Mid-Continent Intensive
MIROC	Model for Interdisciplinary Research on Climate
MODIS	Moderate Resolution Imaging Spectroradiometer
MOPITT	Measurements Of Pollution In The Troposphere
NAA	North American Arctic
NAAC	North American Atlantic Coast
NAAEC	North American Agreement on Environmental Cooperation
NACP	North American Carbon Program
NAO	North Atlantic Oscillation
NAPC	North America Pacific Coast
NASA	National Aeronautics and Space Administration
NASEM	National Academies of Sciences, Engineering, and Medicine
NCA	*National Climate Assessment*
NCA3	*Third National Climate Assessment*
NCA4	*Fourth National Climate Assessment*
NCAR	National Center for Atmospheric Research
NDC	Nationally Determined Contributions
NDVI	normalized difference vegetation index
NECB	net ecosystem carbon balance
NEE	net ecosystem exchange
NEMS	National Energy Modeling System
NEON	National Ecological Observatory Network
NEP	net ecosystem production
NGHGI	National Greenhouse Gas Inventory
NGO	non-governmental organization
NICC	National Indian Carbon Coalition
NIFA	National Institute of Food and Agriculture (USDA)
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NPP	net primary production
NRCS	Natural Resources Conservation Service (USDA)
NSA	North Slope of Alaska
NSF	National Science Foundation
NWCA	National Wetland Condition Assessment
NWI	National Wetlands Inventory

OCO-2	Orbiting Carbon Observatory-2
ODIAC	Open-source Data Inventory for Anthropogenic CO_2
OECD	Organisation for Economic Cooperation and Development
OM	organic matter
OMB	Office of Management and Budget (White House)
OPEC	Organization of Petroleum Exporting Countries
OSTP	Office of Science and Technology Policy (White House)
pCO_2	partial pressure of CO_2
PIC	particulate inorganic carbon
POC	particulate organic carbon
POM	particulate organic matter
PPP	purchasing power parity
PPR	Prairie Pothole Region
PTC	production tax credit
PUC	public utilities commission
PV	photovoltaic
RaCA	Rapid Carbon Assessment
RCP	Representative Concentration Pathway
RD&D	research, development, and demonstration
RE	renewable energy
RECCAP	Regional Carbon Cycle Assessment and Progresses
REDD+	Reducing Emissions from Deforestation and Forest Degradation
RPR (also R/P)	reserve-to-production ratio
RUBISCO	ribulose-1,5-bisphosphate carboxylase oxygenase
SAB	South Atlantic Bight
SCB	Southern California Bight
SD	standard deviation
SE	standard error
SGCR	Subcommittee on Global Change Research (National Science and Technology Council, White House)
SGP	Southern Great Plains
SI	International System of Units
SIF	solar-induced fluorescence
SMR	small mountainous river
SOC	soil organic carbon
SOCCR1	*First State of the Carbon Cycle Report*
SOCCR2	*Second State of the Carbon Cycle Report*
SOM	soil organic matter
SPRUCE	Spruce and Peatland Responses Under Changing Environments
SRES	*Special Report on Emissions Scenarios* (IPCC, 2000)
SS	Scotian Shelf

SSP	Shared Socioeconomic Pathway
SSURGO	Soil Survey Geographic database
STATSGO	State Soil Geographic database
TBM	terrestrial biosphere model
TCCON	Total Carbon Column Observing Network
TCU	tribal colleges and universities
TOC	total organic carbon
TransCom	Atmospheric Tracer Transport Model Intercomparison Project
UCAR	University Corporation for Atmospheric Research
UHI	urban heat island
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
USAID	U.S. Agency for International Development
USDA	U.S. Department of Agriculture
USFWS	U.S. Fish and Wildlife Service
USGCRP	U.S. Global Change Research Program
USGS	U.S. Geological Survey
VOC	volatile organic compound
WRI	World Resources Institute

Abbreviations and Units (partial list)

C	carbon
$CaCO_3$	calcium carbonate
C_2H_6	ethane
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CO_3^{2-}	carbonate ion
COS	carbonyl sulfide
°C	degrees celsius
g	gram
Gt	gigaton
GW	gigawatt
ha	hectare
H_2CO_3	carbonic acid
HCO_3^-	bicarbonate ion
J	Joule
kg	kilogram
µatm	microatmosphere
µm	micrometer
µmol	micromole
MMT	million metric ton
mol	mole
MT	metric ton
MW	megawatt
N	nitrogen
NH_3	ammonia
N_2O	nitrous oxide
NO_x	nitrogen oxides
OH	hydroxyl radical
Pg	petagram
ppb	parts per billion
ppm	parts per million
SF_6	sulfur hexafluoride
SO_x	sulfur oxides
Tg	teragram
W	watt

Appendix G
Glossary

https://doi.org/10.7930/SOCCR2.2018.AppG

A

Adaptation
In human systems, the process of adjusting to an actual or expected environmental change and its effects in a way that seeks to moderate harm or exploit beneficial opportunities. In natural systems, adaptation is the process of adjustment to an actual environmental change and its effects; human intervention may facilitate adjustment to expected changes.

Aerosols
Fine solid particles or liquid droplets suspended in air. They are produced by natural or human activities and can cause cooling by scattering incoming radiation or by affecting cloud cover. Aerosols also can cause warming by absorbing radiation.

Afforestation
The process of establishing trees on land that has lacked forest cover for a very long period of time or land that has never been forested (CCSP 2007).

Related term: *Deforestation*

Agriculture, Forestry, and Other Land Use (AFOLU)
AFOLU plays a central role for food security and sustainable development and is a key greenhouse gas reporting category for national reports to the United Nations Framework Convention on Climate Change. The main carbon mitigation options within AFOLU involve one or more of three strategies: 1) prevention of emissions to the atmosphere by conserving existing carbon pools in soils or vegetation, or by reducing emissions; 2) sequestration—increasing the size of existing land carbon pools, thereby extracting carbon dioxide from the atmosphere for long-term storage; 3) substitution—substituting biological products for fossil fuels or energy-intensive products, thereby reducing carbon dioxide emissions. Demand-side measures (e.g., reduction of food loss and waste, changes in human diet, or changes in wood consumption) also may play a role (Mach et al., 2014).

Related terms: *Forestry and Other Land Use (FOLU); Land Use, Land-Use Change, and Forestry (LULUCF); Greenhouse gas (GHG)*

Albedo
The fraction of solar radiation reflected by a surface or object, often expressed as a percentage. Snow-covered surfaces have a high albedo (highly reflective). Soil albedos range from high to low, and vegetation-covered surfaces and the ocean have a low albedo (low reflectivity). Earth's planetary albedo varies mainly through changes in cloudiness, snow, ice, leaf area, and land cover (Mach et al., 2014).

Algal bloom
A sudden, rapid growth of algae in lakes, estuaries, and ocean waters caused by various factors including warmer surface waters, increased nutrient levels, or increased light levels. Some algal blooms may be toxic or harmful to humans and ecosystems.

Anoxic
A lack of oxygen, usually referring to soils, wetlands, lakes, estuaries, and ocean waters.

Anthropogenic
Caused or influenced by humans; human-induced (CCSP 2007).

Atmospheric column
On average, a column of air with a cross-sectional area of 1 cm^2, measured from mean (average) sea level to the top of Earth's atmosphere. The

column has a mass of about 1.03 kg and exerts a force or "weight" of about 10.1 newtons (N) or 2.37 pounds, resulting in a pressure at sea level of about 10.1 N/cm^2 or 101 kilonewtons (kN)/m^2 (101 kilopascals, kPa).

B

Biodiversity
The variety of life, including the number of plant and animal species, other life forms, genetic types, habitats, and biomes in an ecosystem.

Bioenergy
A form of renewable energy produced from plant and animal biomass.

Bioenergy with Carbon Capture and Storage (BECCS)
A greenhouse gas mitigation technology that reduces carbon dioxide emissions by combining the use of biomass with geological carbon capture and storage (CCS).

Related terms: *Carbon capture and storage (CCS), Carbon sequestration*

Biofuel
Fuel produced from plant or animal matter.

Biogenic emissions
Gaseous emissions from natural sources (e.g., plants, soils, and water bodies).

Biogeochemical cycles
Fluxes, or flows, of chemical elements between Earth's different carbon reservoirs, such as from living to non-living, from atmosphere to land or ocean, from plants to dead organic matter in soils, and from decomposition of organic matter into carbon-containing gases.

Related term: *Carbon reservoir*

Biomass
The mass of living organisms or the material derived from organisms.

Biome
The community of fauna and flora occupying a particular habitat (e.g., Arctic tundra and wetlands).

Biosphere
Parts of the Earth's surface in which living organisms reside.

Black carbon
Soot produced from incomplete combustion of biomass-based materials, such as coal burning, diesel engines, cooking fires, wildfires, and other combustion sources.

Bottom-up method (for estimating greenhouse gas emissions)
Extrapolation of measurements from a single facility or source to larger scales (e.g., regional, national, and global) to produce a bottom-up estimate. Bottom-up approaches also can involve the use of activity data and emissions factors or process-based models.

C

C_3 plant
A plant that uses the Calvin-Benson pathway for "fixing" carbon dioxide, such as during photosynthesis. C_3 refers to the 3-carbon molecule that is the first product of this type of carbon fixation (i.e., living organisms changing inorganic carbon dioxide to organic compounds).

Related terms: *C_4 plant, Carbon fixation*

C_4 plant
A plant that uses the Hatch-Slack pathway for "fixing" carbon dioxide during photosynthesis. C_4 refers to the 4-carbon molecule that is the first product of this type of carbon fixation.

Related terms: *C_3 plant, Carbon fixation*

Carbon allocation
Carbon allocation refers to the partitioning of carbon through different parts of a plant (e.g., stem, roots, and leaves).

Related term: *Stomatal conductance*

Carbon capture and storage (CCS)

The process of capturing carbon and injecting it (as carbon dioxide) into geological formations underground or in the deep ocean for long-term storage.

Related terms: *Bioenergy with Carbon Capture and Storage (BECCS), Carbon sequestration*

Carbon cycle

The series of processes by which carbon compounds flow among reservoirs in the environment, such as the incorporation of carbon dioxide into living tissue by photosynthesis and its return to the atmosphere through respiration, the decay of dead organisms, and the burning of fossil fuels. In the carbon cycle, carbon flow or output from one reservoir transfers carbon to other reservoir(s).

Carbon dioxide (CO_2)

A naturally occurring gas, also a by-product of burning fossil fuels from fossil carbon deposits, such as oil, natural gas, and coal; burning biomass; land-use changes; and industrial processes (e.g., cement production). Carbon dioxide is the principal anthropogenic greenhouse gas that affects Earth's radiative balance. As the reference gas against which other greenhouse gases are measured, it has a global warming potential of 1.

Related terms: *Global warming potential (GWP), carbon dioxide equivalent (CO_2e)*

Carbon dioxide equivalent (CO_2e)

The amount of a gas that would produce the same effect as CO_2 on the radiative balance of Earth's climate system; applicable in this report to greenhouse gases such as methane and nitrous oxide. Outside this report, aerosols and black carbon also influence global warming potential, but translating them to CO_2e values is difficult. The effect on the radiative balance is referred to as the global warming potential, and the time frame over which it is calculated is important because each gas or particle has a different average residence time in the atmosphere. In this report, the time frame over which CO_2e is calculated is assumed to be 100 years, although other time frames may be specified.

Related terms: *Carbon dioxide (CO_2), Global warming potential (GWP)*

Carbon dioxide (CO_2) fertilization

The enhancement of plant growth resulting from increased atmospheric CO_2 concentration (Mach et al., 2014).

Carbon fixation

In this process, also called carbon assimilation, a living organism converts carbon dioxide into an organic compound, such as in photosynthesis.

Related terms: *C3 plant, C4 plant, Photosynthesis*

Carbon flux

Refers to the direction and rate of transfer, or flows, of carbon between pools.

Related terms: *Carbon cycle, Carbon pool, Carbon reservoir, Carbon sink, Carbon source, Carbon stock*

Carbon pool

A compartment, or reservoir, within the Earth system where carbon can be taken up, stored, and/or released within a carbon budget.

Related terms: *Carbon cycle, Carbon flux, Carbon reservoir, Carbon sink, Carbon source, Carbon stock*

Carbon reservoir

A compartment, or pool, within the Earth system where carbon can be taken up, stored, and/or released within a carbon budget.

Related terms: *Carbon cycle, Carbon flux, Carbon pool, Carbon sink, Carbon source, Carbon stock*

Carbon sequestration

Storage of carbon through natural, deliberate, or technological processes in which carbon dioxide is diverted from emissions sources or removed from the atmosphere and stored biologically in the ocean and

terrestrial environments (e.g., vegetation, soils, and sediment), or in geological formations (USGS.gov).

Carbon sink

A compartment within the Earth system that acquires carbon from the atmosphere and stores it for a specified period of time.

Related term: *Carbon cycle, Carbon flux, Carbon pool, Carbon reservoir, Carbon source, Carbon stock*

Carbon source

A compartment within the Earth system that releases carbon to the atmosphere.

Related terms: *Carbon cycle, Carbon flux, Carbon pool, Carbon reservoir, Carbon sink, Carbon stock*

Carbon stock

The mass of carbon contained within a particular compartment, or pool, within the Earth system.

Related terms: *Carbon cycle, Carbon flux, Carbon pool, Carbon reservoir, Carbon sink, Carbon source*

Climate

Climate, in a narrow sense, is usually defined as the average weather, or, more rigorously, as the statistical description in terms of the mean and variability of defining factors over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation, and wind. Climate, in a wider sense, is the state, including a statistical description, of the climate system (modified from Mach et al., 2014).

Climate change

Changes in average weather conditions that persist over multiple decades or longer. Climate change encompasses both increases and decreases in temperature, as well as shifts in precipitation, changes in frequency and location of severe weather events, and changes to other features of the climate system.

Related terms: *Global change, Global warming*

Climate feedback

An interaction in which a perturbation in one climate quantity causes a change in a second quantity, with the change in this second quantity ultimately leading to an additional change in the first. A negative feedback is one in which the initial perturbation is weakened by the changes it causes; a positive feedback is one in which the initial perturbation is enhanced (Mach et al., 2014).

Climate model

A numerical representation of the climate system based on the physical, chemical, and biological properties of its components, their interactions, and feedback processes and accounting for some of its known properties. The climate system can be represented by models of varying complexity; that is, for any one component or combination of components, a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions; the extent to which physical, chemical, or biological processes are explicitly represented; or the level at which empirical parameterizations are involved. Coupled atmosphere-ocean general circulation models provide a representation of the climate system that is near or at the most comprehensive end of the spectrum currently available. There is an evolution toward more complex models with interactive chemistry and biology. Climate models are applied as a research tool to study and simulate the climate and for operational purposes, including monthly, seasonal, and interannual climate predictions (Mach et al., 2014).

Climate projection

The simulated response of the climate system to a scenario of future emissions or concentrations of greenhouse gases and aerosols, generally derived using climate models. Climate *projections* are distinguished from climate *predictions* by their dependence on the emissions, concentration, or radiative forcing scenario used, which, in turn, is based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized (Mach et al., 2014).

Related terms: *Climate, Climate model*

Climate variability
Natural changes in climate that fall within the observed range of extremes for a particular region, as measured by temperature, precipitation, and frequency of events. Drivers of climate variability include the El Niño–Southern Oscillation and other phenomena.

Related terms: *El Niño–Southern Oscillation (ENSO), La Niña*

Coastal ocean
The portion of the ocean that is influenced by land. Definitions vary considerably. In this report, the coastal ocean is defined as nonestuarine waters within 200 nautical miles (370 km) of the coast.

Co-benefits
The positive effects that a policy or measure aimed at one objective might have on other objectives, irrespective of the net effect on overall social welfare. Co-benefits are often subject to uncertainty and depend on local circumstances and implementation practices, among other factors. Co-benefits also are referred to as ancillary benefits (Mach et al., 2014).

Continental shelves
The submerged margins of the continental plates, operationally defined in this report as regions with water depths shallower than 200 m.

Coupled Model Intercomparison Project (CMIP)
The Coupled Model Intercomparison Project is a standard experimental protocol for studying the output of coupled atmosphere-ocean general circulation models. Phases three and five (CMIP3 and CMIP5, respectively) coordinated and archived climate model simulations based on shared model inputs by modeling groups from around the world. The CMIP3 multimodel dataset includes projections using the scenarios drawn from the Intergovernmental Panel on Climate Change's Special Report on emissions scenarios. The CMIP5 dataset includes projections using the Representative Concentration Pathways (edited from Mach et al., 2014).

Cryosphere
All regions on and beneath the surface of the Earth and ocean where water is in solid form, including sea ice, lake ice, river ice, snow cover, glaciers, ice sheets, and frozen ground (e.g., permafrost) (Mach et al., 2014).

D

Deforestation
The process of removing or clearing trees from forested land with lasting conversion of that land to nonforest (CCSP 2007).

Related term: *Afforestation*

Denitrification
The microbial reduction of nitrate to dinitrogen gas and nitrous oxide.

Dissolved inorganic carbon (DIC)
The sum of inorganic oxidized carbon species in a solution, including carbon dioxide, carbonic acid, bicarbonate anions, and carbonate anions.

Related term: *Dissolved organic carbon (DOC)*

Dissolved organic carbon (DOC)
Dissolved organic carbon refers to the sum of organic reduced carbon species in a solution (e.g., organic and humic acids). Dissolved organic matter (DOM) refers to the entire chemical compound, while DOC refers only to the carbon fraction. Both DOM and DOC typically are operationally defined as less than 0.45 micrometers and thus may include chemical species that are colloidal and not truly dissolved.

Related terms: *Particulate organic carbon (POC), Dissolved inorganic carbon (DIC)*

Downscaling
A method that derives local- to regional-scale (10 to 100 km) climate information from larger-scale models or data analyses. Two main methods exist. Dynamical downscaling uses the output of regional climate models, global models with variable spatial resolution, or high-resolution global models. Empir-

ical or statistical downscaling methods develop statistical relationships that link the large-scale atmospheric variables with local or regional climate variables. In all cases, the quality of the driving model remains an important limitation on the quality of the downscaled information (Mach et al., 2014).

Drought

A period of abnormally dry weather marked by little or no rain that lasts long enough to cause water shortage for people and natural systems.

E

Earth System Model (ESM)

A coupled atmosphere-ocean general circulation model in which a representation of the carbon cycle is included, allowing for interactive calculation of atmospheric carbon dioxide or compatible emissions. Additional components (e.g., atmospheric chemistry, ice sheets, dynamic vegetation, nitrogen cycle, and urban or crop models) may be included (Mach et al., 2014).

Ecosystem

A functional unit consisting of living organisms, their nonliving environment, and the interactions within and between them. The components included in a given ecosystem and its spatial boundaries depend on the purpose for which the ecosystem is defined. In some cases, ecosystem boundaries are relatively sharp, while in others they are diffuse, and they can change over time. Ecosystems are nested within other ecosystems, and their scale can range from very small to the entire biosphere. In the current era, most ecosystems either contain people as key organisms, or they are influenced by the effects of human activities in their environment (Mach et al., 2014).

Related term: *Ecosystem services*

Ecosystem services

The benefits produced by ecosystems on which people depend, including, for example, fisheries, drinking water, fertile soils for growing crops, climate regulation, and aesthetic and cultural value.

Related term: *Ecosystem*

Ecotone

A region of transition between two biological communities or biomes.

Edaphic

Produced by or influenced by the soil. Edaphic qualities may refer to characteristics of the soil itself (e.g., texture or chemical properties). Edaphic qualities also may refer to other ecosystem compartments such as microbial or plant communities that are influenced by soil properties.

Efficiency gap

The difference between a predicted rate of an economically attractive purchase of more efficient technology and lower actual realized adoption rates.

El Niño–Southern Oscillation (ENSO)

A natural interaction between surface air pressure and surface water temperature in the tropical Pacific Ocean. ENSO has two phases: the warm oceanic phase, El Niño, accompanies high surface air pressure in the western Pacific, while the cold phase, La Niña, accompanies low surface air pressure in the western Pacific. Each phase generally lasts 6 to 18 months. ENSO events occur irregularly, about every 3 to 7 years. The extremes of this climate oscillation cause extreme weather (such as floods and droughts) in many regions of the world.

Related term: *La Niña*

Embedded carbon

Carbon fluxes resulting from the production of goods or services typically consumed.

Embeddedness of carbon

The condition that carbon is an integral but often invisible part of how people lead their lives, so they do not think of themselves as using carbon but

instead see the services and products without seeing their embedded carbon.

Embodied carbon

Carbon residing in material typically released to the atmosphere upon decay or disintegration (e.g., cardboard and construction lumber).

Emissions scenarios

Quantitative illustrations of how the release of different amounts of climate-altering gases and particles into the atmosphere from human and natural sources will produce different future climate conditions. The Intergovernmental Panel on Climate Change developed a Special Report on emissions scenarios (IPCC 2000) using a wide range of assumptions about population growth, economic and technological development, and other factors. An A1B emissions scenario is a medium future emissions scenario in which greenhouse gas emissions increase, with reductions in the rate of increase in emissions after 2070. An A2 emissions scenario is a high future emissions scenario assuming continued increases in greenhouse gas emissions. The B1 emissions scenario is a lower future emissions scenario in which emissions are reduced rapidly and substantially. The B2 emissions scenario is a low future emissions scenario in which emissions are reduced substantially, but not as rapidly as B1.

Related term: *Representative Concentration Pathway (RCP)*

Energy end use

Energy used for services such as transportation, cooking, indoor thermal comfort, refrigeration, and illumination.

Energy intensity

The ratio of energy use to economic or physical output (Mach et al., 2014).

Energy supply

The processes for extracting energy resources and converting them into more desirable and suitable forms of secondary energy, and for delivering energy to places where demand exists (Grubler et al., 2013).

Energy systems

The infrastructure and systems of electricity production, transport, storage, and consumption.

Enteric methane

Methane generated in the gastrointestinal tract; the term is predominantly used to denote methane originating from microbial fermentation in the pregastric compartments of the digestive system of ruminant animals.

Environmental justice

The fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies.

Estuary

A body of water in which river water and ocean water mix. The landward boundary of an estuary is defined in this report as the location (also known as the head-of-tide) where tidal fluctuations become very small. The seaward boundary of an estuary is less clearly defined, but it may be determined based on salinity, bathymetry, or coastline position.

Eutrophication

Enrichment of water by nutrients such as nitrate, ammonia, and phosphate, and thus supporting a dense concentration of primary producers, resulting in an increase in primary production. It is one of the leading causes of water quality impairment. The two most acute symptoms of eutrophication are hypoxia (a state of oxygen depletion) and harmful algal blooms (Mach et al., 2014).

Related term: *Hypoxia*

Evapotranspiration

Evaporation of water from soils, plants, and free water surfaces exposed to the atmosphere.

Exclusive Economic Zone (EEZ)

A zone in the ocean typically extending 200 km or less away from the coast of a nation. Oceanic carbon dioxide uptake or loss is not credited to any nation under Intergovernmental Panel on Climate Change carbon dioxide accounting rules.

Extreme event

A weather event that is rare at a particular place and time of year, including, for example, heatwaves, cold waves, heavy rains, periods of drought and flooding, and severe storms. Definitions of rare vary, but an extreme weather event would normally be as rare as or rarer than the 10% or 90% probability density function estimated from observations. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense (Mach et al., 2014).

F

Feedback

The process through which a system is controlled, changed, or modulated in response to its own output. Positive feedback results in amplification of the system output; negative feedback reduces the output of a system.

Related term: *Climate feedback*

Final energy

Energy transported and distributed to the point of retail for delivery to final users (e.g., firms, individuals, or institutions; Grubler et al., 2013).

First Nations

Indigenous communities in Canada.

Food security

When all people always have both physical and economic access to sufficient food to meet their dietary needs for a productive and healthy life.

Forcing

A perturbation to a factor that affects Earth's climate. For example, both volcanoes and humans emit heat-trapping gases and particles through volcanic emissions and through fossil fuel combustion, respectively, which can perturb Earth's climate.

Forestry and Other Land Use (FOLU)

The subset of Agriculture, Forestry, and Other Land Use (AFOLU) emissions and removals of greenhouse gases resulting from direct human-induced land use, land-use change, and forestry activities excluding agricultural emissions (Mach et al., 2014).

Related terms: *Agriculture, Forestry, and Other Land Use (AFOLU); Land Use, Land-Use Change, and Forestry (LULUCF); Greenhouse gas (GHG)*

Fossil fuels

Fuels such as coal, petroleum, and natural gas derived primarily from the chemical and physical transformation (fossilization) of the remains of plants and animals that lived during previous times (CCSP 2007).

Fugitive emissions

Emissions of gases or vapors from pressurized equipment due to leaks and other unintended or irregular releases, typically from industrial, drilling, or mining activities. Fugitive emissions contribute to air pollution and climate change (e.g., methane gas is readily lost during transport through pipelines or during oil drilling activities), as well as the economic cost of lost commodities.

Related term: *Leakage*

G

Geoengineering

Intentional modifications of the Earth system, usually technological, to reduce future climate change.

Global change

Changes in the global environment. Global change encompasses climate change, but it also includes other critical drivers of environmental change that may interact with climate change, such as land-use

change, alteration of the water cycle, changes in biogeochemical cycles, and biodiversity loss. Global change may alter the capacity of the Earth to sustain life.

Related terms: *Climate change, Global warming*

Global warming

The observed increase in average temperature near Earth's surface and in the lowest layer of the atmosphere. In common usage, global warming often refers to the warming that has occurred because of increased emissions of greenhouse gases from human activities. Global warming is a type of climate change; it also can lead to other changes in climate conditions, such as changes in precipitation patterns.

Global warming potential (GWP)

An index, based on radiative properties of different greenhouse gases, measuring the radiative forcing following a pulse emission of a unit mass of a given greenhouse gas in the present-day atmosphere integrated over a chosen time horizon, relative to the radiative forcing of carbon dioxide. The carbon dioxide GWP is 1. A GWP represents the combined effect of the differing times a given gas remains in the atmosphere and its relative effectiveness in causing radiative forcing over a specified time frame. In this report, the time frame is assumed to be 100 years, but it may be specified according to other time frames (truncated from Mach et al., 2014).

Related term: *Carbon dioxide equivalent (CO_2e)*

Governance

The processes and structures that steer society and the multiplicity of actors who are involved. Institutional arrangements of governance comprise the sets of rules, norms, and shared practices that underlie decision making.

Greenhouse gas (GHG)

Gases that absorb heat in the atmosphere near Earth's surface, preventing it from escaping into space. If the atmospheric concentrations of these gases rise, the average temperature of the lower atmosphere will gradually increase, a phenomenon known as the greenhouse effect. Greenhouse gases include, for example, carbon dioxide, nitrous oxide, water vapor, and methane.

Gross primary production (GPP)

The gross uptake of carbon dioxide through photosynthesis.

Related term: *Net primary production (NPP)*

H

Halocarbon

A chlorofluorocarbon or other compound in which the hydrogen of a hydrocarbon is replaced by halogens (i.e., group VIIA of the periodic table including fluorine, bromine, and chlorine).

Hydrocarbon

A compound composed of hydrogen and carbon (e.g., petroleum products and fossil fuels).

Hypoxia

Deficiency of oxygen in water bodies defined as oxygen concentrations less than 2 milligrams per liter. Hypoxia can be a symptom of eutrophication (nutrient overloading). Deoxygenation (the process of removing oxygen) leads to hypoxia and the expansion of oxygen minimum zones (modified from Mach et al., 2014).

Related term: *Eutrophication*

I

Ionophore

Ionophores are feed additives used in cattle diets to increase feed efficiency and body weight gain. They are compounds that alter rumen fermentation patterns. Ionophores can be fed to any class of cattle and can be used in any segment of the beef cattle industry (Hershom and Thrift 2012).

Indicator

An observation or calculation that allows scientists, analysts, decision makers, and others to track

environmental trends, understand key factors that influence the environment, and identify effects on ecosystems and society.

Indigenous communities

Those who, having a historical continuity with preinvasion and precolonial societies that developed on their territories, consider themselves distinct from other sectors of the societies now prevailing on those territories, or parts of them. They form at present nondominant sectors of these societies and are determined to preserve, develop, and transmit to future generations their ancestral territories and ethnic identities, as the basis of their continued existence as peoples, in accordance with their own cultural patterns, social institutions, and legal system (Mach et al., 2014).

Indirect fluxes

Fluxes associated with energy used to create or deliver electricity, products, or services consumed in a given area or the carbon flux associated with waste decay or removal of material to the waste stream.

Inland waters

Open-water systems of lakes, reservoirs, nontidal rivers, and streams in noncoastal environments.

Integrated assessment

A method of analysis that combines results and models (e.g., Integrated Assessment Models) from the physical, biological, economic, and social sciences and the interactions among these components in a consistent framework to evaluate the status and consequences of environmental change and the policy responses to it (Mach et al., 2014).

L

La Niña

A natural interaction between surface air pressure and surface water temperature in the tropical Pacific Ocean. El Niño–Southern Oscillation (ENSO) has two phases: the cold phase, La Niña, accompanies low surface air pressure in the western Pacific, while the warm oceanic phase, El Niño, accompanies high surface air pressure in the western Pacific. Each phase generally lasts 6 to 18 months. ENSO events occur irregularly, about every 3 to 7 years. The extremes of this climate oscillation cause extreme weather (such as floods and droughts) in many regions of the world.

Related term: *El Niño–Southern Oscillation*

Land cover

The physical characteristics of the land surface such as crops, trees, or concrete.

Land use

Activities taking place on land, such as growing food, cutting trees, or building cities.

Leakage

Can refer to leakage of methane or other gases during drilling and storage and during transfers through pipelines. Leakage also can refer to the situation in which a carbon sequestration activity (e.g., tree planting or avoided deforestation) on one piece of land inadvertently, directly or indirectly, triggers an activity, which in whole or in part counteracts the carbon effects of the initial activity (modified from CCSP 2007).

Related term: *Fugitive emissions*

Lock-in

Occurs when a market is stuck with a standard even though participants would be better off with an alternative. In this report, lock-in is used more broadly as path dependence, which is the generic situation where decisions, events, or outcomes at one point in time constrain adaptation, mitigation, or other actions or options at a later point in time (Mach et al., 2014).

Land Use, Land-Use Change, and Forestry (LULUCF)

Land Use, Land-Use Change, and Forestry (LULUCF)—also referred to as FOLU (Forestry and Other Land Use)—is the subset of Agriculture, Forestry, and Other Land Use (AFOLU) emissions

and removals of greenhouse gases resulting from direct, human-induced land use, land-use change, and forestry activities excluding agricultural emissions (Mach et al., 2014).

Related terms: *Agriculture, Forestry, and Other Land Use (AFOLU); Forestry and Other Land Use (FOLU); Greenhouse gas (GHG)*

M

Marine boundary layer

The marine atmospheric boundary layer is the part of the atmosphere that has direct physical and material interaction with the ocean and, hence, is directly influenced by the ocean. Thus, the marine boundary layer is where the ocean and atmosphere exchange large amounts of heat, moisture, and momentum, primarily via turbulent transport (Sikora and Ufermann 2004).

Mesosphere

The layer of Earth's atmosphere directly above the stratosphere. Boundaries vary with season and latitude, beginning approximately 50 to 65 km above Earth's surface and extending to about 85 to 100 km.

Mitigation

Measures to reduce the amount and rate of future climate change by reducing emissions of heat-trapping gases or removing carbon dioxide from the atmosphere.

Monomictic lake

A lake that is mixed from top to bottom during one mixing period per year. Monomictic lakes are found in both warm and cold regions.

N

Native American

Member of an Indigenous community in the American continents.

Net ecosystem carbon balance (NECB)

The net rate of carbon accumulation in (or loss from [negative sign]) ecosystems. NECB represents the overall ecosystem carbon balance from all sources and sinks—physical, biological, and anthropogenic (Chapin et al., 2006).

Net ecosystem exchange (NEE)

The net flux of carbon dioxide to the land from the atmosphere. Positive values refer to carbon released to the atmosphere (i.e., a source), and negative values refer to carbon uptake (i.e., a sink; Hayes and Turner 2012).

Net ecosystem production (NEP)

The net carbon imbalance within an ecosystem between uptake of carbon dioxide from gross primary production and release of carbon dioxide from autotrophic and heterotrophic respiration; by convention, positive NEP values represent net carbon dioxide uptake by the ecosystem, and negative values represent the net release of carbon dioxide (Chapin et al., 2006).

Net primary production (NPP)

The net uptake of carbon dioxide by plants through gross primary production in excess of losses from plant, or autotrophic, respiration (CCSP 2007).

Related term: *Gross primary production (GPP)*

Nutrients

Chemicals such as nitrate, ammonium, and phosphate that plants and animals need to live and grow. At high concentrations, particularly in water, nutrients can become pollutants.

Nutrient-use efficiency

Nutrient-use efficiency usually is measured in terms of yield per concentration of added nutrients. The concept is most applicable to agricultural situations but can refer to any plant.

O

Ocean acidification

The process by which the pH measurement of ocean water has moved toward more acidic levels due to the absorption of human-produced carbon dioxide,

which interacts with ocean water to form carbonic acid, thereby lowering the pH. Increased acidity reduces the ability of plankton and shelled animals to form and maintain carbonate-containing body parts such as shells.

Ozone

A colorless gas consisting of three atoms of oxygen, readily reacting with many other substances. Ozone in the upper atmosphere protects Earth from harmful levels of ultraviolet radiation from the sun. In the lower atmosphere, ozone is an air pollutant with harmful effects on human health.

P

Particulate organic carbon (POC)

Colloidal particles of organic carbon in a solution, typically operationally defined as being greater than 0.45 micrometers. Particulate organic matter (POM) refers to the entire chemical compound, while POC refers only to the elemental carbon fraction.

Related term: *Dissolved organic carbon (DOC)*

Pathogen

Microorganisms, such as a bacteria or viruses, that cause disease.

Peatlands

Areas having a soil organic layer thickness of at least 40 cm (CCSP 2007).

Permafrost

Ground that remains at or below freezing (0°C) for at least two consecutive years.

pH

A dimensionless measure of the acidity of water (or any solution) given by its concentration of hydrogen ions (H^{+}). pH is measured on a logarithmic scale where pH = –log10(H^{+}), where the concentration of hydrogen ions is measured in units of moles per liter. Thus, a pH decrease of 1 unit corresponds to a 10-fold increase in the concentration of H+, or acidity (Mach et al., 2014).

Phenology

The pattern of seasonal life cycle events in plants and animals, such as timing of blooming, hibernation, and migration.

Photosynthesis

The process by which green plants, algae, and other organisms use sunlight to synthesize energy from carbon dioxide and water. Photosynthesis in plants generally involves the green pigment chlorophyll, consumes carbon dioxide and water, and generates oxygen as a by-product.

Phytoplankton

Microscopic plants that live in salt water and freshwater environments.

Planetary boundary layer

The lowest part of the atmosphere. The layer has direct physical and material interaction with a planetary surface.

Related term: *Marine boundary layer*

Primary energy

Energy extracted or captured directly from resources as they exist in nature. Primary energy is typically divided into three distinct groups: nonrenewable energy (e.g., fossil fuels such as coal, crude oil, natural gas, and other fuels such as nuclear); renewable energy (e.g., hydropower, biomass, solar energy, wind, geothermal, and ocean energy); and waste. Primary energy is not used directly but is converted and transformed into secondary energy such as electricity and fuels such as gasoline, jet fuel, or heating oils.

Priming

Priming or the "priming effect" is said to occur when something added to soil or compost affects the rate of microbial decomposition of soil organic matter, either positively or negatively. Organic matter is made up mostly of carbon and nitrogen, so adding a substrate containing certain ratios of these nutrients to soil may

affect the microbes that are mineralizing soil organic matter. Fertilizers, plant litter, detritus, and carbohydrate exudates from living roots potentially can positively or negatively prime SOM decomposition.

Related terms: *Soil organic matter (SOM), Nutrients*

Proven reserves (coal, oil, shale, and natural gas)

Reserves of fossil fuels in the Earth that are economically profitable to recover using current technologies.

Related term: *Unproven reserves*

Proxy

Indirect measurement of climate aspects. Examples of proxy data are biological or physical records from ice cores, tree rings, and soil boreholes.

R

Radiative effects, radiative forcing

The change in the net (downward minus upward) radiative flux (expressed in watts per m^2 (W/m^2) at the tropopause or top of the atmosphere caused by a change in an external driver of climate change, such as a change in the concentration of carbon dioxide or in the output of the sun (truncated from Mach et al., 2014).

Rebound effect

The case in which expected savings from technology adoption may not be realized because of choices, behaviors, and intervening developments not predicted by efficiency intervention planners.

Reforestation

The process of establishing a new forest by planting or seeding trees in an area where trees have previously been removed.

Related terms: *Afforestation, Deforestation*

Representative Concentration Pathway (RCP)

Scenarios that include time series of emissions scenarios and concentrations of the full suite of greenhouse gases, aerosols, and chemically active gases, as well as land use and land cover. The word "representative" signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. The term "pathway" emphasizes that of interest are not only the long-term concentration levels, but also the trajectory taken over time to reach that outcome. RCPs usually refer to the portion of the concentration pathway extending up to the year 2100. Four RCPs produced from Integrated Assessment Models were selected from the published literature for use in the *Intergovernmental Panel on Climate Change Fifth Assessment Report:* RCP2.6, a pathway whereby radiative forcing peaks at approximately 3 watts per m^2 (W/m^2) before 2100 and then declines; RCP4.5 and RCP6.0, two intermediate stabilization pathways in which radiative forcing is stabilized at approximately 4.5 W/m^2 and 6.0 W/m^2, respectively, after 2100; and RCP8.5, a high emissions pathway for which radiative forcing reaches greater than 8.5 W/m^2 by 2100 and continues to rise for some amount of time (truncated and adapted from Mach et al., 2014).

Related terms: *Emissions scenarios; Integrated assessment; Radiative effects, radiative forcing*

Resilience

The capacity of social, economic, and environmental systems to cope with a hazardous event, trend, or disturbance. It is measured in ways that systems respond or reorganize to maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation (truncated and adapted from Mach et al., 2014).

Respiration

Metabolic pathways that break down complex molecules to release chemically stored energy for maintenance, growth, and reproduction, resulting in the release of waste products such as carbon dioxide, nitrous oxide, or methane.

Rhizosphere

The environment in soils near the root zone of plants.

Risk
Threats to life, health, and safety; the environment; economic well-being; and other things of value. Risks are evaluated in terms of how likely they are to occur (probability) and the damages that would result if they did happen (consequences).

Rumen
The largest segment of ruminant animals' complex stomach, in which methanogenic archaea generate methane (predominantly) from hydrogen and carbon dioxide.

S

Scenario
Set of assumptions used to help understand plausible future conditions such as population growth, land use, and sea level rise. Scenarios are neither predictions nor forecasts, and they are commonly used for planning purposes.

Related term: *Emissions scenarios*

Sink
A physical location where carbon is removed from the atmosphere and stored, either through natural or technological processes. Entire ecosystems, specific ecosystem components (e.g., forest and soil), or political boundaries may be characterized as a sink.

Related terms: *Carbon sink, Carbon source*

Snowpack
Snow that accumulates over winter and slowly melts to release water in spring and summer.

Social network analysis
A method that maps the connections among people who have links to one another in a common area of concern.

Social practice theory
A perspective that focuses on activities engaged in by people to accomplish goals as a principal way of understanding behavior in a social context.

Socioecological systems
Nested, multilevel systems that provide essential services to society such as supply of food, fiber, energy, and drinking water (Berkes and Folke 1998).

Sociotechnical transitions analysis
A method that includes both social and technical aspects for understanding why technological change occurs and whether change can be steered and accelerated.

Soil organic carbon (SOC)
The organic carbon content of soil organic matter (SOM). SOM and SOC in soil result from an imbalance between the supply of raw materials, such as plant, microbial, and animal parts, and the decay of those materials by the soil microbial community.

Related term: *Soil organic matter (SOM)*

Soil organic matter (SOM)
Organic material (e.g., carbon and other elements such as nitrogen in soils). SOM results from an imbalance between the supply of raw materials such as plant, microbial, and animal parts and the decay of those materials by the soil microbial community. SOM forms the basis of life on Earth, enabling persistence and growth of the entire biosphere and can be considered in terms of its carbon content (e.g., soil organic carbon).

Related term: *Soil organic carbon (SOC)*

Source
A physical location from which carbon is released to the atmosphere, either through natural or technological processes. Entire ecosystems, specific ecosystem components (e.g., forest or soil), or political boundaries may be characterized as a source.

Related terms: *Carbon sink, Carbon source, Sink*

Stakeholder
An individual or group that is directly or indirectly affected by or interested in the outcomes of decisions.

Stomatal conductance

The rate of passage of carbon dioxide entering, or water vapor exiting, through the stomata (pores) of a leaf.

Related term: *Transpiration*

Storm surge

The temporary increase, at a particular locality, in the height of the sea due to extreme meteorological conditions (low atmospheric pressure and/or strong winds). The storm surge is defined as being the excess above the level expected from the tidal variation alone at that time and place (Mach et al., 2014).

Stratification

The layering of water by temperature and salinity, which affect the density of water. Layering can occur in ocean waters, estuaries, lakes, and other water bodies, and it may be long term or undergo seasonal changes.

Stratosphere

The second major layer of Earth's atmosphere, residing above the troposphere and below the mesosphere. Near the equator, the stratosphere starts at 18 km; at midlatitudes, it starts at 10 to 13 km and ends at 50 km; at the poles, it starts at about 8 km.

Related terms: *Mesosphere, Troposphere*

Stressor

A factor that affects people and natural, managed, and socioeconomic systems. Multiple stressors can have compounded effects, such as when economic or market stress combines with drought to negatively impact farmers.

Related term: *Drought*

Surface energy balance

A statement of the conservation of energy applied to a given surface. For Earth's surface, the main terms are the vertical fluxes into or out of the surface due to net radiation, sensible heat, and latent heat, as well as the net horizontal fluxes of energy that may take place below the surface (e.g., due to ocean currents). Any nonzero residual flux typically is applied as a storage term, increasing or decreasing the internal energy below the surface and usually resulting in an associated change of surface temperature (AMS 2018).

T

Thermohaline circulation

A part of the large-scale ocean circulation that is driven by global density gradients created by surface heat and freshwater fluxes.

Thermokarst

The process by which characteristic landforms result from the thawing of ice-rich permafrost or the melting of massive ground ice (Mach et al., 2014).

Threshold

The value of a parameter summarizing a system, or a process affecting a system, at which a qualitatively different system behavior emerges. Beyond this value, the system may not conform to statistical relationships that described it previously. For example, beyond a threshold level of ocean acidification, wide-scale collapse of coral ecosystems may occur (USGCRP 2017).

Tipping point

The point at which a change in the climate triggers a significant environmental event, which may be permanent, such as widespread bleaching of corals or the melting of very large ice sheets.

Related terms: *Threshold, Forcing*

Top-down method (for estimating greenhouse gas emissions)

Approaches based on atmospheric measurements that are directed toward estimating emissions from regions that could include multiple facilities (Heath et al., 2015).

Traditional knowledge
The knowledge, innovations, and practices of Indigenous and local communities around the world. Developed from experience gained over the centuries and adapted to the local culture and environment, traditional knowledge generally is transmitted orally from generation to generation and often is used as a synonym for Indigenous or local knowledge (Mach et al., 2014).

Transpiration
The evaporation of water through plant leaves.

Related term: *Stomatal conductance*

Trend
A systematic change over time (CCSP 2007).

Troposphere
The lowest region of the atmosphere, extending from Earth's surface to a height of about 6 to 18 km, which is the lower boundary of the stratosphere. The troposphere is the lowest layer of Earth's atmosphere where nearly every weather condition takes place. It contains approximately 75% of the atmosphere's mass and 99% of the total mass of water vapor and aerosols.

Related terms: *Mesosphere, Stratosphere*

Tundra
A type of biome common to extreme northern latitudes where tree growth is inhibited by low temperatures and short growing seasons.

U

Uncertainty
An expression of the degree to which a quantity or process is unknown. In statistics, a term used to describe the range of possible values around a best estimate, sometimes expressed in terms of probability or likelihood. Uncertainty about the future climate arises from the complexity of the climate system and the ability of models to represent it, as well as the inability to predict the decisions that society will make. There also is uncertainty about how climate change, in combination with other stressors, will affect people and natural systems.

United Nations Framework Convention on Climate Change (UNFCC)
An international environmental treaty adopted on May 9, 1992, and ratified on March 21, 1994. The objective of the UNFCC is to stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.

Unproven reserves
Reserves of fossil fuels in the Earth that are economically unprofitable to recover using current technologies.

Related term: *Proven reserves*

Urban heat island effect
The tendency for higher air temperatures to persist in urban areas because of heat absorbed and emitted by buildings and asphalt, tending to make cities warmer than the surrounding countryside.

Urban infrastructure
Materials and organization structures and facilities needed for the operation of urban living (e.g., roads, buildings, public transit, and pipelines).

V

Validate
To establish or verify accuracy. For example, using measurements of temperature or precipitation to determine the accuracy of climate model results.

Value
Belief or ideal held by individuals or society about what is important or desirable.

Value (economic)
The benefit, usually expressed in monetary terms, gained from use or enjoyment from a good or service.

Vector (disease)

An organism, such as an insect, that transmits disease-causing microorganisms such as viruses or bacteria. Vector-borne diseases include, for example, malaria, dengue fever, and lyme disease.

Vulnerability

The degree to which physical, biological, and socioeconomic systems are susceptible to and unable to cope with adverse impacts of climate change.

Vulnerability assessment

An analysis of the degree to which a system is susceptible to or unable to cope with the adverse effects of climate change.

W

Water-use efficiency

Refers to the ratio of carbon uptake through plant productivity to water lost by the plant through evapotranspiration.

Related terms: *Evapotranspiration, Transpiration*

Water stress

Water stress occurs when demand for water by people and ecosystems exceeds available supply.

Wetlands

Soils that are inundated or saturated by water at a frequency and duration sufficient to support, and that do support under normal circumstances, a prevalence of vegetation typically adapted for life in saturated conditions (U.S. EPA 2015). Tidal wetlands are influenced by ocean tides and may be saturated with salt water or freshwater. Terrestrial wetlands are nontidal and are saturated with freshwater.

Woody encroachment

Refers to woody plants colonizing grasslands or other nonforested ecosystems.

Y

Yedoma

An organic-rich (about 2% carbon by mass) Pleistocene-age permafrost sediment with ice content of 50% to 90% by volume.

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Braided river delta in Lower Cook Inlet, Kachemak Bay, Alaska. The rate of exchange of carbon dioxide and methane between land and coastal waters and between the land and atmosphere is accelerating due to the warming climate in the high latitudes. Such climate change–induced shifts in the carbon cycle across the region are assessed in pertinent chapters throughout the *Second State of the Carbon Cycle Report*, including Ch. 11: Arctic and Boreal Carbon.

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