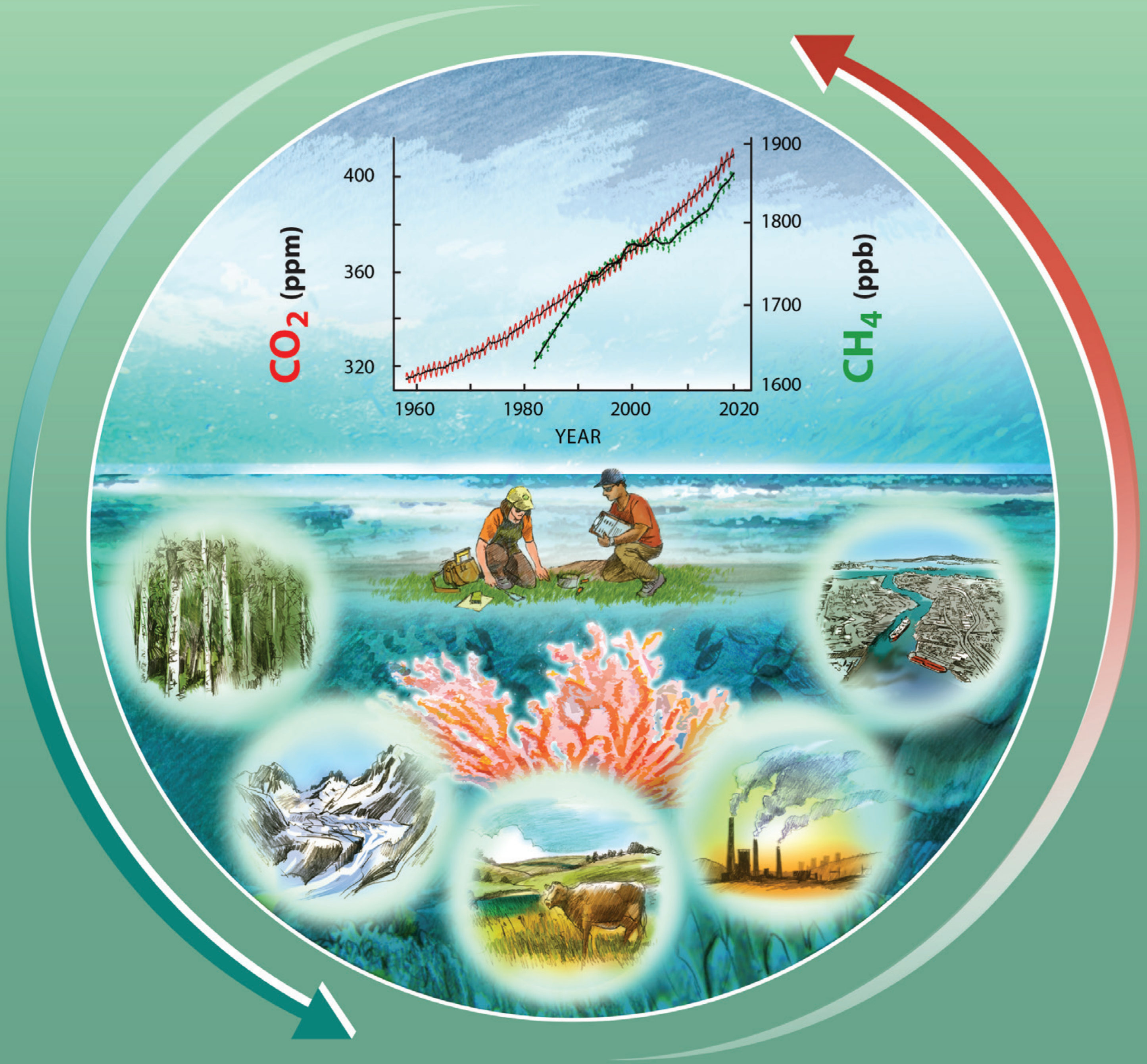
Second State of the Carbon Cycle Report



Report in Brief

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About this Report in Brief

This document presents components of the *Second State of the Carbon Cycle Report* (SOCCR2), including Highlights, the Executive Summary, and contributors and acknowledgments. The entire SOCCR2 report consists of four interconnected sections (I. Synthesis; II. Human Dimensions of the Carbon Cycle; III. State of Air, Land, and Water; and IV. Consequences and Ways Forward) that encompass 19 chapters followed by seven appendices across 878 pages.

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).

Second State of the Carbon Cycle Report

Report in Brief

U.S. Global Change Research Program

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 America

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.

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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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. 7).

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. 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. 8.

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 organic compounds that make up all living things. Essential for fundamental human activities and

[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.]

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. 10). 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. 11, and Ch. 1: Overview of the Global Carbon Cycle).

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 (Ch. 19: Future of the North American Carbon Cycle).

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. 10; Ch. 2: The North American Carbon Budget; and Ch. 8: Observations of Atmospheric Carbon Dioxide and Methane). 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. 11) 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), expanding renewable energy use,

[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.

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; Ch. 3: Energy Systems).

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. (More details on alternatives for carbon accounting and emissions attribution are in SOCCR2's Preface and Appendix D: Carbon Measurement Approaches and Accounting Frameworks.)

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, Hawaiʻi; 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.

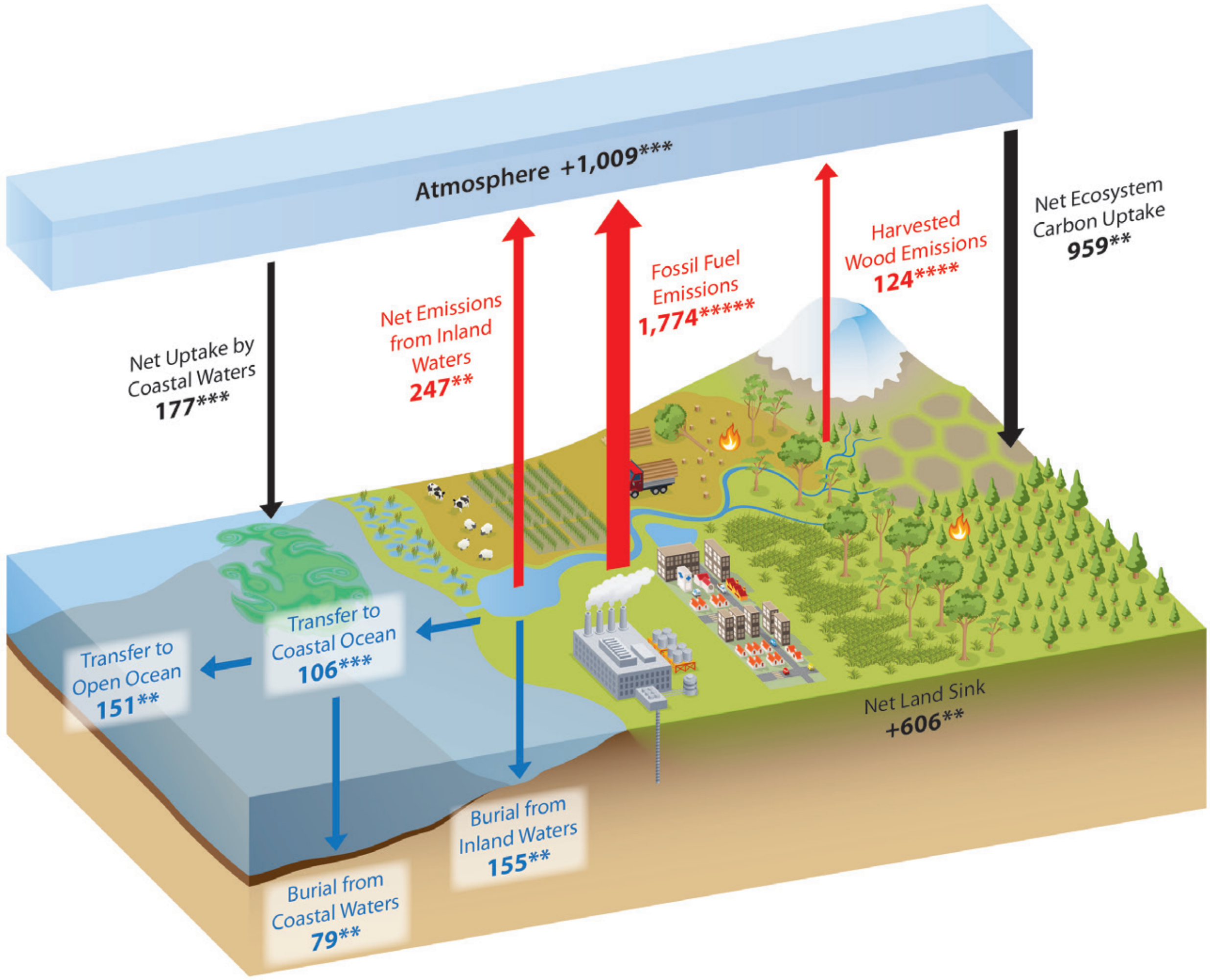

Figure ES.2. Major Carbon Fluxes of North America. Net fluxes and transfers of carbon among the atmosphere, land, and water are depicted in this simplified representation of the North American carbon cycle. The diagram includes fluxes of carbon dioxide but not methane or other carbon-containing greenhouse 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. 11, and Figure 2.3 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, 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. 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.]

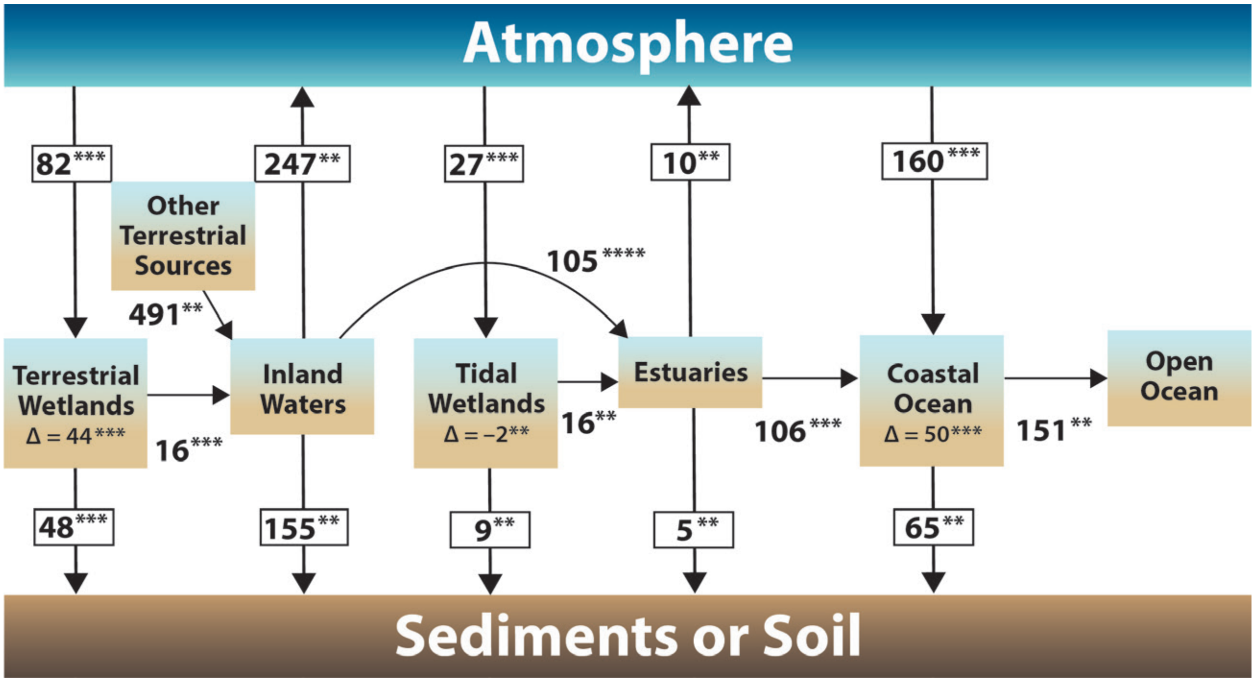

Figure ES.3. Total Carbon Budget of North American Aquatic Ecosystems. Flux estimates, in teragrams of carbon (Tg C) per year, are derived from Ch. 13: Terrestrial Wetlands, Ch. 14: Inland Waters, Ch. 15: Tidal Wetlands and Estuaries, and Ch. 16: Coastal Ocean and Continental Shelves. Carbon exchanges 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 (Ch. 17: Biogeochemical Effects of Rising Atmospheric Carbon Dioxide). 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 GHGs is

[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.

largely responsible for Earth's increased temperature over the past 100 years. The global mean temperature in 2017 relative to the 1880 to1920 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 (Ch. 8: Observations of Atmospheric Carbon Dioxide and Methane). 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 (Ch. 1: Overview of the Global Carbon Cycle). 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 (Ch. 19: Future of the North American Carbon Cycle).

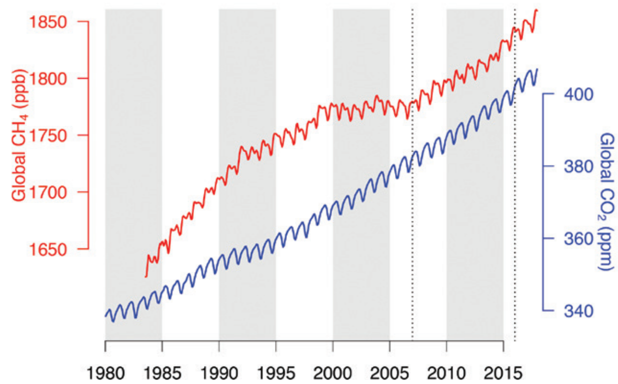

Figure ES.4. Global Monthly Mean Atmospheric Methane (CH_4) and Carbon Dioxide (CO_2) Concentrations. CH_4 values (red) and CO_2 values (blue) are averaged from the background surface sites of the National Oceanic and Atmospheric Administration's global monitoring network. Dotted vertical lines in 2007 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.]

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 (Ch. 1: Overview of the Global Carbon Cycle). 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.

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.

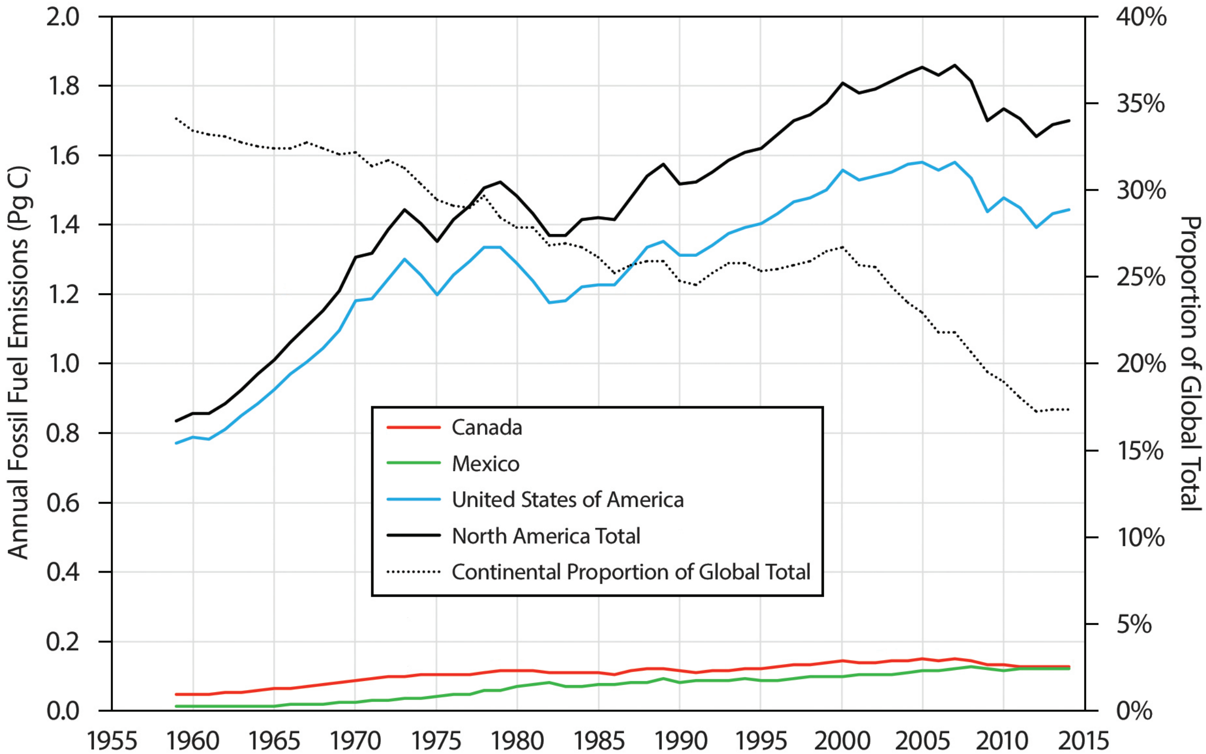

Figure ES.5. Annual North American Fossil Fuel Emissions from 1959 to 2014. Values are given in petagrams of carbon (Pg C) for each country and for the continent as a whole (solid lines, left vertical axis). The dotted line shows the North American proportion of total global emissions (right vertical axis). [From Figure 2.2 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. 10). 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 (Ch. 3: Energy Systems). 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; Ch. 3: Energy Systems; and Ch. 8: Observations of Atmospheric Carbon Dioxide and Methane).

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. 10; Figure ES.3, p. 11; and Ch. 14: Inland Waters). 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%; Ch. 14 and Ch. 15: Tidal Wetlands and Estuaries). The transfer from the coastal ocean to the open ocean is estimated to be 151 Tg C per year (±70%; Ch. 16: Coastal Ocean and Continental Shelves). 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. 11). 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).

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, and Ch. 15). Terrestrial wetlands are a natural source of CH_4 (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 (Ch. 2: The North American Carbon Budget). 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. 10). 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 (Ch. 2 and Ch. 8: Observations of Atmospheric Carbon Dioxide and Methane).

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 (Ch. 16: Coastal Ocean and Continental Shelves).

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 (Table 2.1 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 (Ch. 12: Soils). 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 (Ch. 11: Arctic and Boreal Carbon).

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 (Ch. 9: Forests). Across the continent, afforestation added 27 Tg C per year and deforestation led to a loss of 38 Tg C per year (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 (Ch. 5: Agriculture). 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 (Ch. 2: The North American Carbon Budget and Ch. 11: Arctic and Boreal Carbon). 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 (Ch. 17: Biogeochemical Effects of Rising Atmospheric Carbon Dioxide). Rising atmospheric CO_2 has decreased seawater pH, leading to ocean acidification as evidenced from measurements at long-term observing stations around North America (Ch. 16: Coastal Ocean and Continental Shelves 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 (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 (Ch. 17: Biogeochemical Effects of Rising Atmospheric Carbon Dioxide). 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

[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 in the SOCCR2 Preface for details.

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 (Ch. 12: Soils). 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 (Ch. 17).

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 (Ch. 3–10). 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 (Ch. 3: Energy Systems), but society also uses carbon in other less obvious ways such as food and buildings. Carbon is thus embedded in social life (Ch. 6: Social Science Perspectives on Carbon), 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. 17, and Ch. 18: Carbon Cycle Science in Support of Decision Making). 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 and Ch. 18). 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. 13; Ch. 2: The North American Carbon Budget; and Ch. 3: Energy Systems). Social mechanisms have influenced carbon emissions through acceptance of rooftop solar energy 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

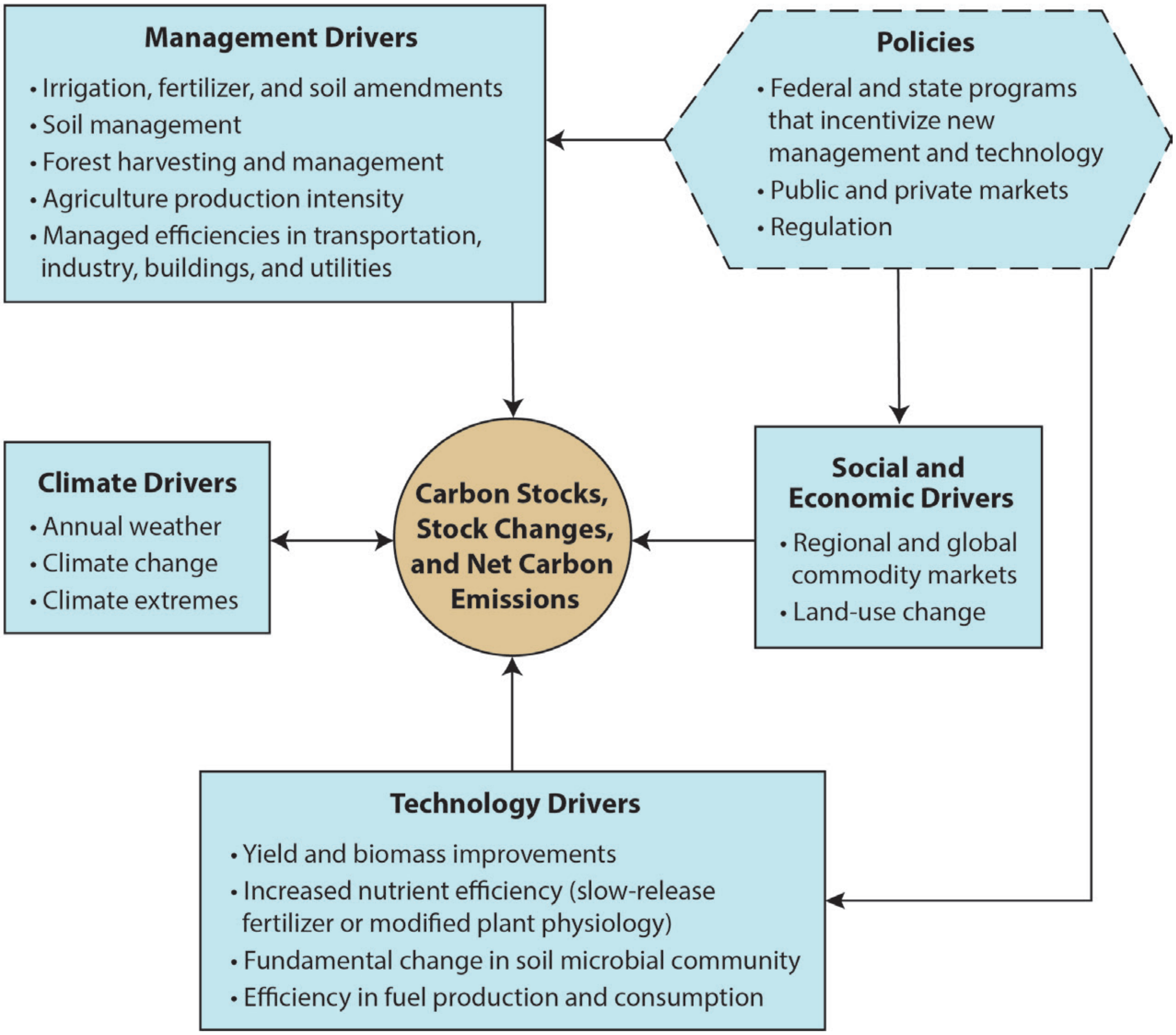

Figure ES.6. Primary Drivers of Carbon Stocks and Emissions in Select Sectors. Efforts to understand and estimate future carbon stocks and emissions require considering and representing the factors that drive their change. This schematic illustrates examples of components needed to represent carbon stock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

practices (Ch. 6: Social Science Perspectives on Carbon). 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 (Ch. 3: Energy Systems).

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 (Ch. 4: Understanding Urban Carbon Fluxes). 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 (Ch. 5: Agriculture). 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 (Ch. 7: Tribal Lands).

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 (Ch. 9: Forests).

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. 19).

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 (Ch. 19: Future of the North American Carbon Cycle). Projections include the combined effects of policies, technologies, prices, economic 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

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 (Ch. 1: Overview of the Global Carbon Cycle and Ch. 3: Energy Systems). 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 (Ch. 19: Future of the North American Carbon Cycle).

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 (Ch. 19).

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 (Ch. 11: Arctic and Boreal Carbon, Ch. 12: Soils, and Ch. 19: Future of the North American Carbon Cycle).

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 (Ch. 19). 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 (Ch. 1: Overview of the Global Carbon Cycle). 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. 21). To help reduce emissions, subnational entities in North America have implemented activities such as green building codes and efforts related to regional energy systems (Ch. 3: Energy Systems).

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

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 (Ch. 1: Overview of the Global Carbon Cycle). 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 (Ch. 6: Social Science Perspectives on Carbon). 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 (Ch. 6). With this 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 (Ch. 3: Energy Systems, Ch. 6, and Ch. 18: Carbon Cycle Science in Support of Decision Making).

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 (Ch. 3: Energy Systems and Ch. 4: Understanding Urban Carbon Fluxes). 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.

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 (Ch. 3: Energy Systems).

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 (Ch. 4: Understanding Urban Carbon Fluxes). 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 (Ch. 3).

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 (Ch. 5: Agriculture, Ch. 9: Forests, Ch. 10: Grasslands, and Ch. 12: Soils). 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 (Ch. 12).

Grazing and Livestock Management. These management activities affect grassland carbon stocks and their net carbon uptake by tens of teragrams per year (Ch. 10). 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 (Ch. 5).

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 (Ch. 5 and Ch. 12).

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 (Ch. 13: Terrestrial Wetlands and Ch. 15 Tidal Wetlands and Estuaries). 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 (Ch. 7: Tribal Lands). 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 (Ch. 3: Energy Systems).

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 (Ch. 4: Understanding Urban Carbon Fluxes). 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 (Ch. 9: Forests). 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 (Ch. 12: Soils). 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 (Ch. 10: Grasslands).

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 (Ch. 7: Tribal Lands).

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. 17, and Ch. 18: Carbon Cycle Science in Support of Decision Making). 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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Chapter 2: The North American Carbon Budget

Hayes, D. J., R. **Vargas**, S. R. Alin, R. T. Conant, L. R. Hutyra, A. R. Jacobson, W. A. Kurz, S. Liu, A. D. McGuire, B. Poulter, and C. W. Woodall.

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Chapter 3: Energy Systems

Marcotullio, P. J., L. Bruhwiler, S. Davis, J. Engel-Cox, J. Field, C. Gately, K. R. Gurney, D. M. Kammen, E. McGlynn, J. McMahon, W. R. Morrow, III, I. B. Ocko, and R. Torrie.

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Chapter 4: Understanding Urban Carbon Fluxes

Gurney, K. R., P. **Romero-Lankao**, S. **Pincetl**, M. Betsill, M. Chester, F. Creutzig, K. Davis, R. Duren, G. Franco, S. Hughes, L. R. Hutyra, C. Kennedy, R. Krueger, P. J. Marcotullio, D. Pataki, D. Sailor, and K. V. R. Schäfer.

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Chapter 5: Agriculture

Hristov, A. N., J. M. F. **Johnson**, C. W. Rice, M. E. Brown, R. T. Conant, S. J. Del Grosso, N. P. Gurwick, C. A. Rotz, U. M. Sainju, R. H. Skinner, T. O. West, B. R. K. Runkle, H. Janzen, S. C. Reed, N. Cavallaro, and G. Shrestha.

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Chapter 6: Social Science Perspectives on Carbon

Malone, E. L., M. Betsill, S. Hughes, R. Kemp, L. Lutzenhiser, M. Moezzi, B. L. Preston, and T. O. West.

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Chapter 7: Tribal Lands

McCarthy, M. I., B. Ramsey, J. Phillips, and M. H. Redsteer.

https://doi.org/10.7930/SOCCR2.2018.Ch7.

Chapter 8: Observations of Atmospheric Carbon Dioxide and Methane

Jacobson, A. R., J. B. **Miller**, A. Ballantyne, S. Basu, L. Bruhwiler, A. Chatterjee, S. Denning, and L. Ott.

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Chapter 9: Forests

Domke, G., C. A. **Williams**, R. Birdsey, J. Coulston, A. Finzi, C. Gough, B. Haight, J. Hicke, M. Janowiak, B. de Jong, W. A. Kurz, M. Lucash, S. Ogle, M. Olguín-Álvarez, Y. Pan, M. Skutsch, C. Smyth, C. Swanston, P. Templer, D. Wear, and C. W. Woodall.

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Chapter 10: Grasslands

Pendall, E., D. Bachelet, R. T. Conant, B. El Masri, L. B. Flanagan, A. K. Knapp, J. Liu, S. Liu, and S. M. Schaeffer.

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Chapter 11: Arctic and Boreal Carbon

Schuur, E. A. G., A. D. **McGuire**, V. **Romanovsky**, C. Schädel, and M. Mack.

https://doi.org/10.7930/SOCCR2.2018.Ch11.

Chapter 12: Soils

Lajtha, K., V. L. **Bailey**, K. McFarlane, K. Paustian, D. Bachelet, R. Abramoff, D. Angers, S. A. Billings, D. Cerkowniak, Y. G. Dialynas, A. Finzi, N. H. F. French, S. Frey, N. P. Gurwick, J. Harden, J. M. F. Johnson, K. Johnson, J. Lehmann, S. Liu, B. McConkey, U. Mishra, S. Ollinger, D. Paré, F. Paz Pellat, D. deB. Richter, S. M. Schaeffer, J. Schimel, C. Shaw, J. Tang, K. Todd-Brown, C. Trettin, M. Waldrop, T. Whitman, and K. Wickland.

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Chapter 13: Terrestrial Wetlands

Kolka, R., C. **Trettin**, W. Tang, K. Krauss, S. Bansal, J. Drexler, K. Wickland, R. Chimner, D. Hogan, E. J. Pindilli, B. Benscoter, B. Tangen, E. Kane, S. Bridgham, and C. Richardson.

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Chapter 14: Inland Waters

Butman, D., R. Striegl, S. Stackpoole, P. del Giorgio, Y. Prairie, D. Pilcher, P. Raymond, F. Paz Pellat, and J. Alcocer.

https://doi.org/10.7930/SOCCR2.2018.Ch14.

Chapter 15: Tidal Wetlands and Estuaries

Windham-Myers, L., W.-J. **Cai**, S. R. Alin, A. Andersson, J. Crosswell, K. H. Dunton, J. M. Hernandez-Ayon, M. Herrmann, A. L. Hinson, C. S. Hopkinson, J. Howard, X. Hu, S. H. Knox, K. Kroeger, D. Lagomasino, P. Megonigal, R. G. Najjar, M.-L. Paulsen, D. Peteet, E. Pidgeon, K. V. R. Schäfer, M. Tzortziou, Z. A. Wang, and E. B. Watson.

https://doi.org/10.7930/SOCCR2.2018.Ch15.

Chapter 16: Coastal Ocean and Continental Shelves

Fennel, K., S. R. Alin, L. Barbero, W. Evans, T. Bourgeois, S. R. Cooley, J. Dunne, R. A. Feely, J. M. Hernandez-Ayon, C. Hu, X. Hu, S. E. Lohrenz, F. Muller-Karger, R. G. Najjar, L. Robbins, J. Russell, E. H. Shadwick, S. Siedlecki, N. Steiner, D. Turk, P. Vlahos, and Z. A. Wang.

https://doi.org/10.7930/SOCCR2.2018.Ch16.

Chapter 17: Biogeochemical Effects of Rising Atmospheric Carbon Dioxide

Cooley, S. R., D. J. P. **Moore**, S. R. Alin, D. Butman, D. W. Clow, N. H. F. French, R. A. Feely, Z. I. Johnson, G. Keppel-Aleks, S. E. Lohrenz, I. B. Ocko, E. H. Shadwick, A. J. Sutton, C. S. Potter, Y. Takatsuka, A. P. Walker, and R. M. S. Yu.

https://doi.org/10.7930/SOCCR2.2018.Ch17.

Chapter 18: Carbon Cycle Science in Support of Decision Making

West, T. O., N. P. Gurwick, M. E. Brown, R. Duren, S. Mooney, K. Paustian, E. McGlynn, E. L. Malone, A. Rosenblatt, N. Hultman, and I. B. Ocko.

https://doi.org/10.7930/SOCCR2.2018.Ch18.

Chapter 19: Future of the North American Carbon Cycle

Huntzinger, D. N., A. **Chatterjee**, D. J. P. Moore, S. Ohrel, T. O. West, B. Poulter, A. P. Walker, J. Dunne, S. R. Cooley, A. M. Michalak, M. Tzortziou, L. Bruhwiler, A. Rosenblatt, Y. Luo, P. J. Marcotullio, and J. Russell.

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Back Cover

Alaska ShoreZone Program, courtesy Mandy Lindeberg, Alaska Fisheries Science Center within the National Oceanic and Atmospheric Administration's National Marine Fisheries Service.

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 SOCCR2, including Ch. 11: Arctic and Boreal Carbon.

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