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

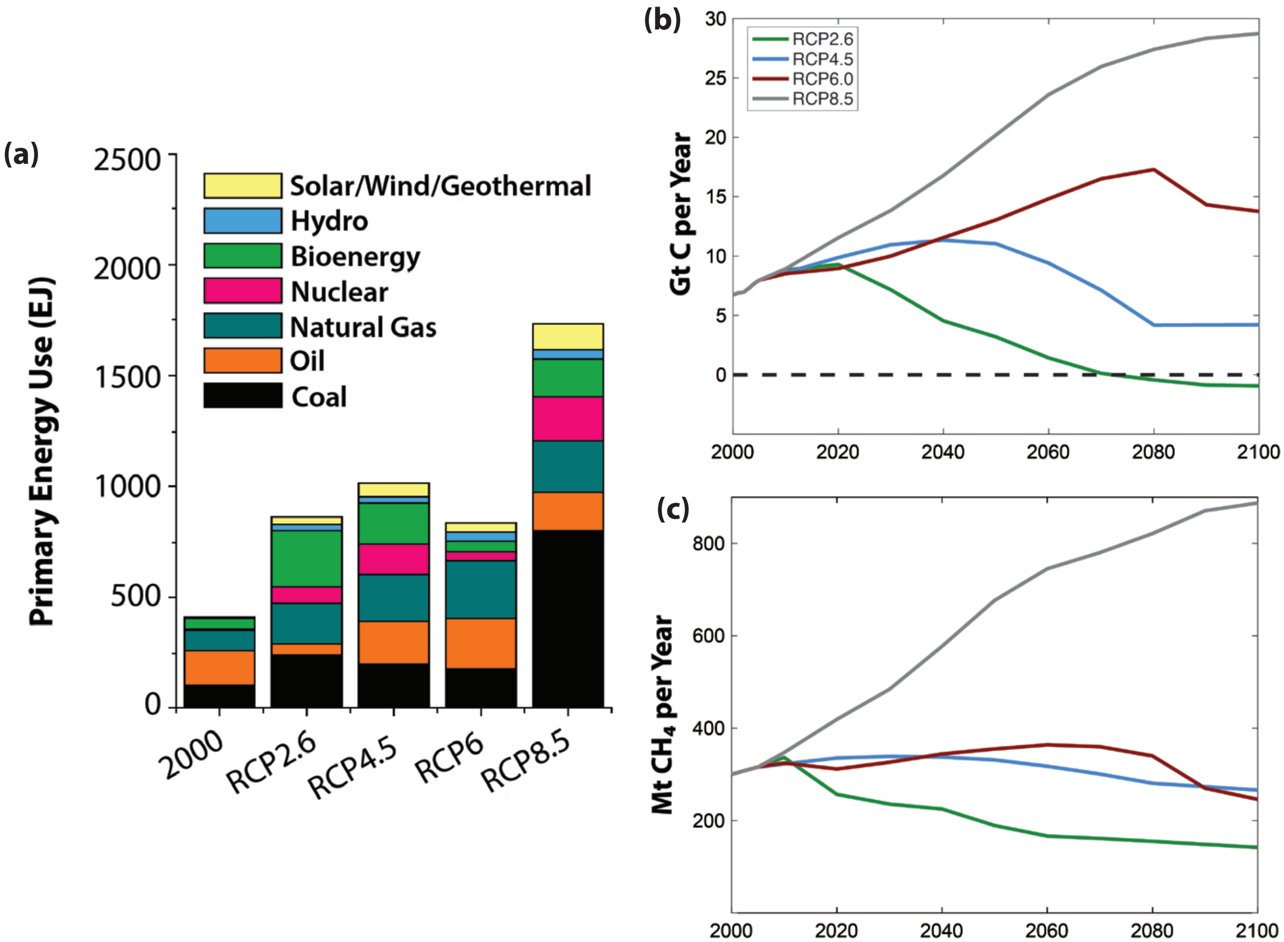

Figure 19.1. Projected Global Energy Consumption and Emissions. Projections of **(a)** primary energy consumption in exajoules (EJ) by source and emissions of **(b)** carbon dioxide measured in gigatons of carbon (Gt C) and **(c)** methane (CH_4) measured in megatons (Mt) under the four different Representative 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

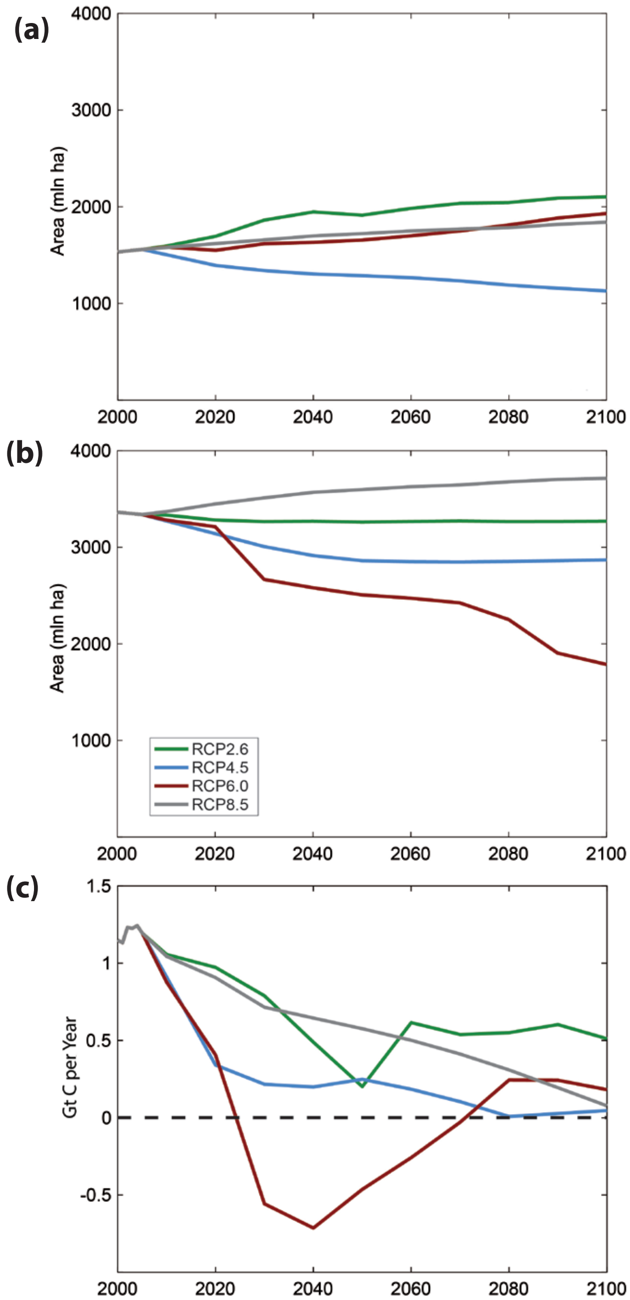

Figure 19.2. Projections of Future Land-Use Area and Land-Use Emissions. Projections of land-use area in hectares (ha) for **(a)** croplands and **(b)** grasslands, along with **(c)** carbon dioxide emissions related to land use measured in gigatons of carbon (Gt C) under the four Representative Concentration 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

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(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

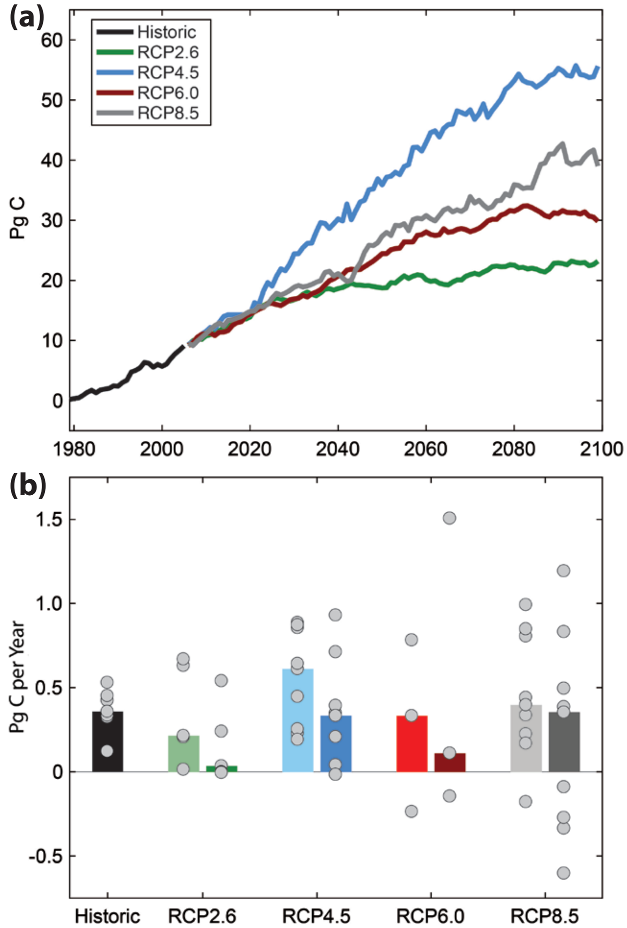


Figure 19.3. Projected Cumulative and Net Land Carbon Sink for North America Based on Four Future Scenarios. (a) Historic and projected cumulative North American land carbon sinks are shown in petagrams of carbon (Pg C) from 1980 to 2099 for the ensemble median under each Representative Concentration 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

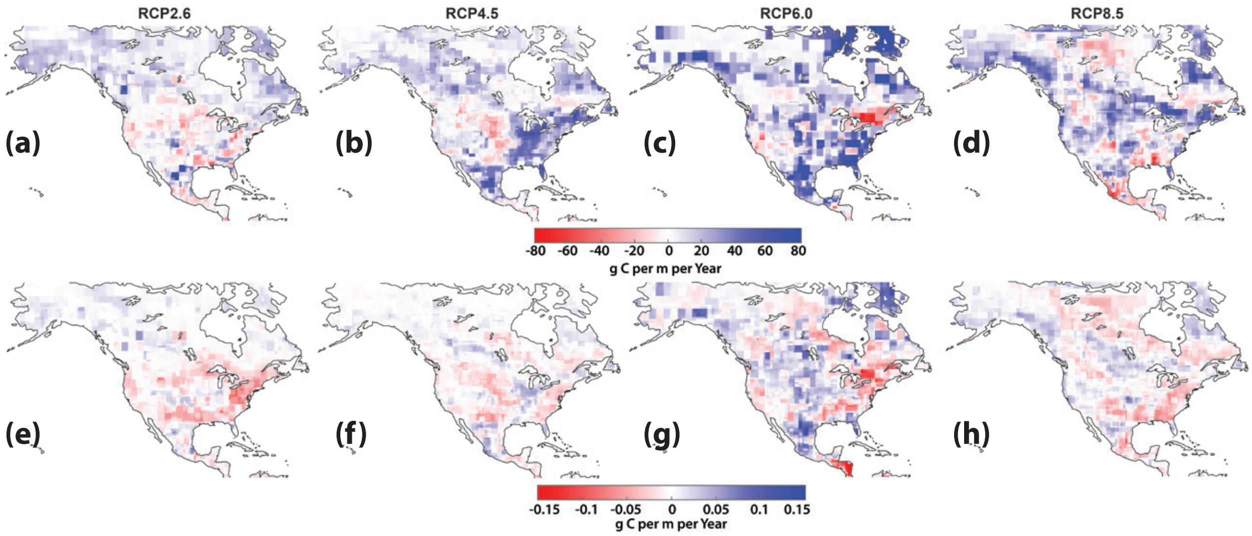


Figure 19.4. Projected Decadal Median Net Land Carbon Sink for North America Based on Four Future Scenarios. (a–d) Projected decadal median land carbon sink in grams of carbon (g C) for North America from 2090 to 2099 under each Representative Concentration Pathway (RCP) scenario: **(a)** RCP2.6, **(b)** 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

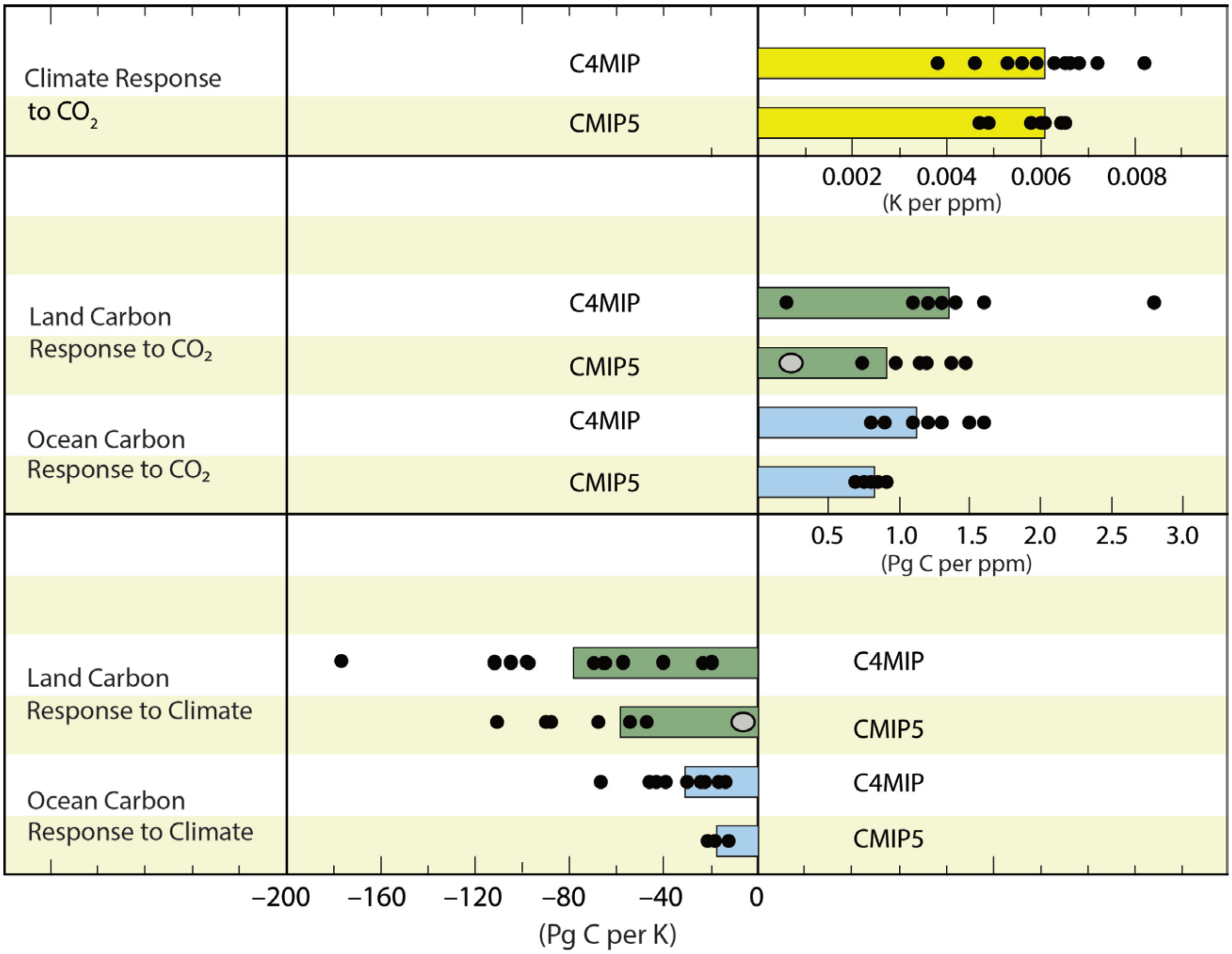


Figure 19.5. Land and Ocean Carbon Cycle Feedbacks from Two Generations of Coupled Carbon-Climate Models. The large uncertainty in carbon cycle response to climate and rising atmospheric carbon dioxide (CO_2) is shown, particularly for the land carbon cycle. Uncertainty in the response of the ocean carbon 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

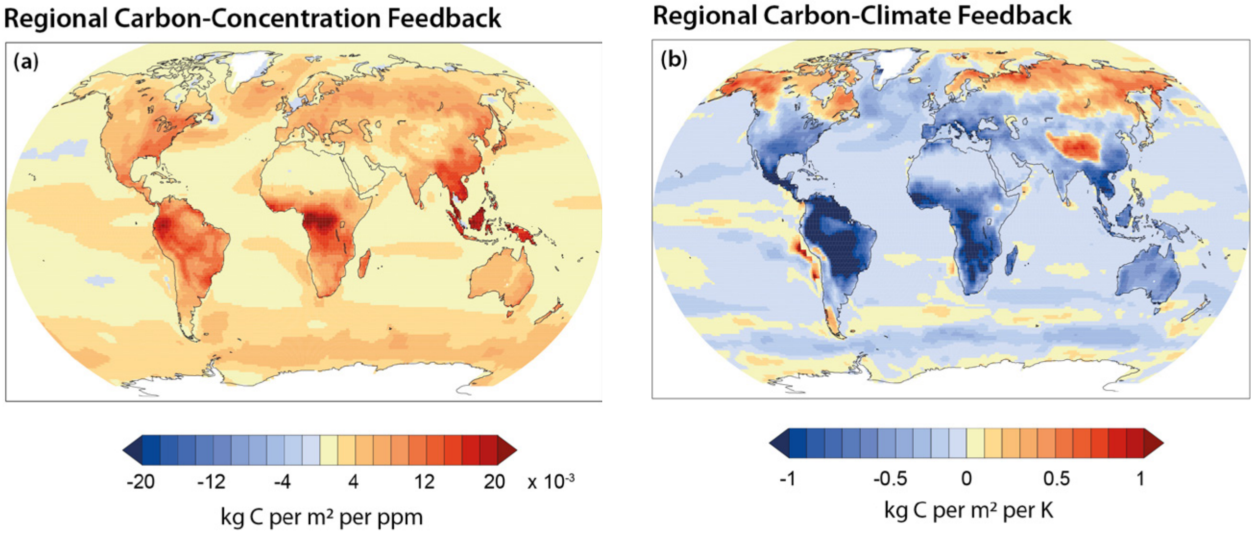


Figure 19.6. Simulated Spatial Distribution of Land and Ocean Carbon Sink Sensitivity to (a) Rising Atmospheric Carbon Dioxide (CO_2) and (b) a Warming Climate. Shows the change in land carbon storage and air-sea carbon exchange based on a quadrupling of atmospheric CO_2 concentrations relative to global 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,

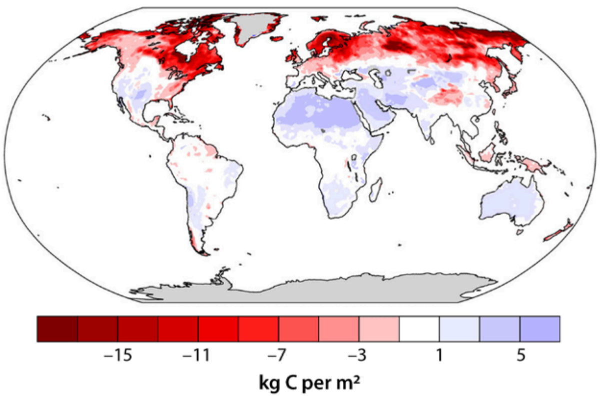


Figure 19.7. Potential Vulnerability of Soil Carbon Stocks to Climate Warming. This map, based on a meta-analysis of warming experiments, shows predicted changes in soil carbon stocks by 2050 using spatially explicit estimates of these stocks (measured in kilograms of carbon per square meter [kg C per m^2]) and changes in soil surface temperature. Changes are for surface soil carbon stocks (0 to 15 cm in depth) under a 1ºC 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

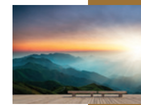
Within North America, rising atmospheric CO_2 is projected to increase ocean and coastal carbon uptake almost everywhere, particularly in the North Atlantic, which shows the strongest uptake response (see Figure 19.5, p. 775). Rising atmospheric CO_2 concentrations have changed the chemical partitioning 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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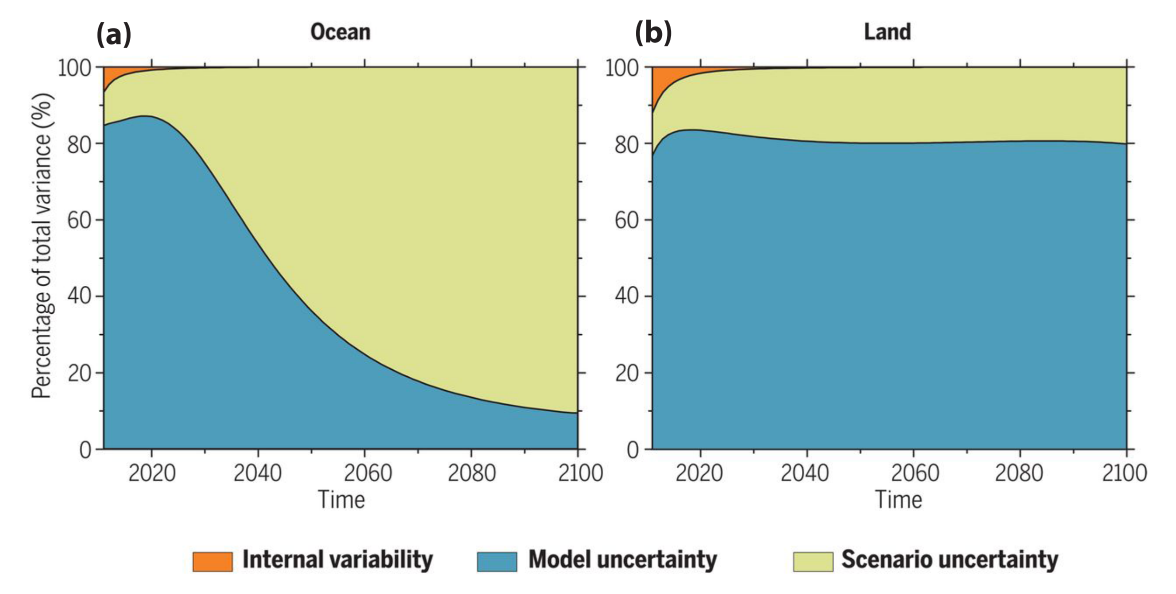

Figure 19.8. Ocean and Land Carbon Cycle Uncertainty. The percentage of total model variance or spread attributed to internal variability, model uncertainty, and scenario uncertainty in projections of cumulative global carbon uptake differs widely between **(a)** ocean and **(b)** land. The ocean carbon 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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