Section I
SYNTHESIS

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

1 Overview of the Global Carbon Cycle

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KEY FINDINGS

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

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

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

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

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

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

1.1 The Role of Carbon in the Earth System

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

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

Box 1.1 Why a Global Carbon Cycle Context

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

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

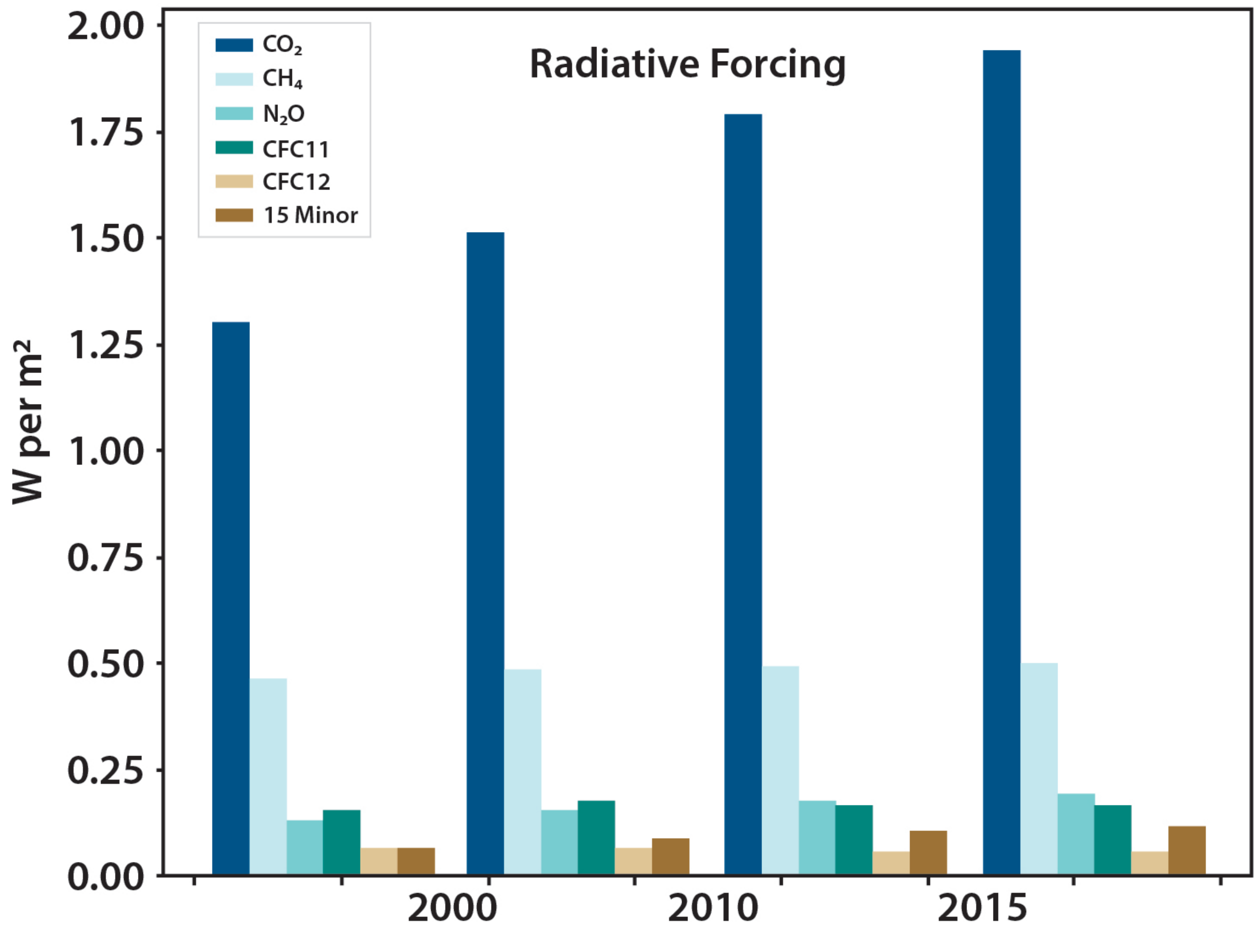


Figure 1.1. Radiative Forcing (Relative to 1750) Due to Major Greenhouse Gases (GHGs). Major GHGs include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), trichlorofluoromethane (CFC11), and dichlorodifluoromethane (CFC12). The 15 minor GHGs include CFC-113; CCl_4; CH_3CCl_3; HCFCs 22, 141b,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

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

1.2 The Natural Carbon Cycle

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

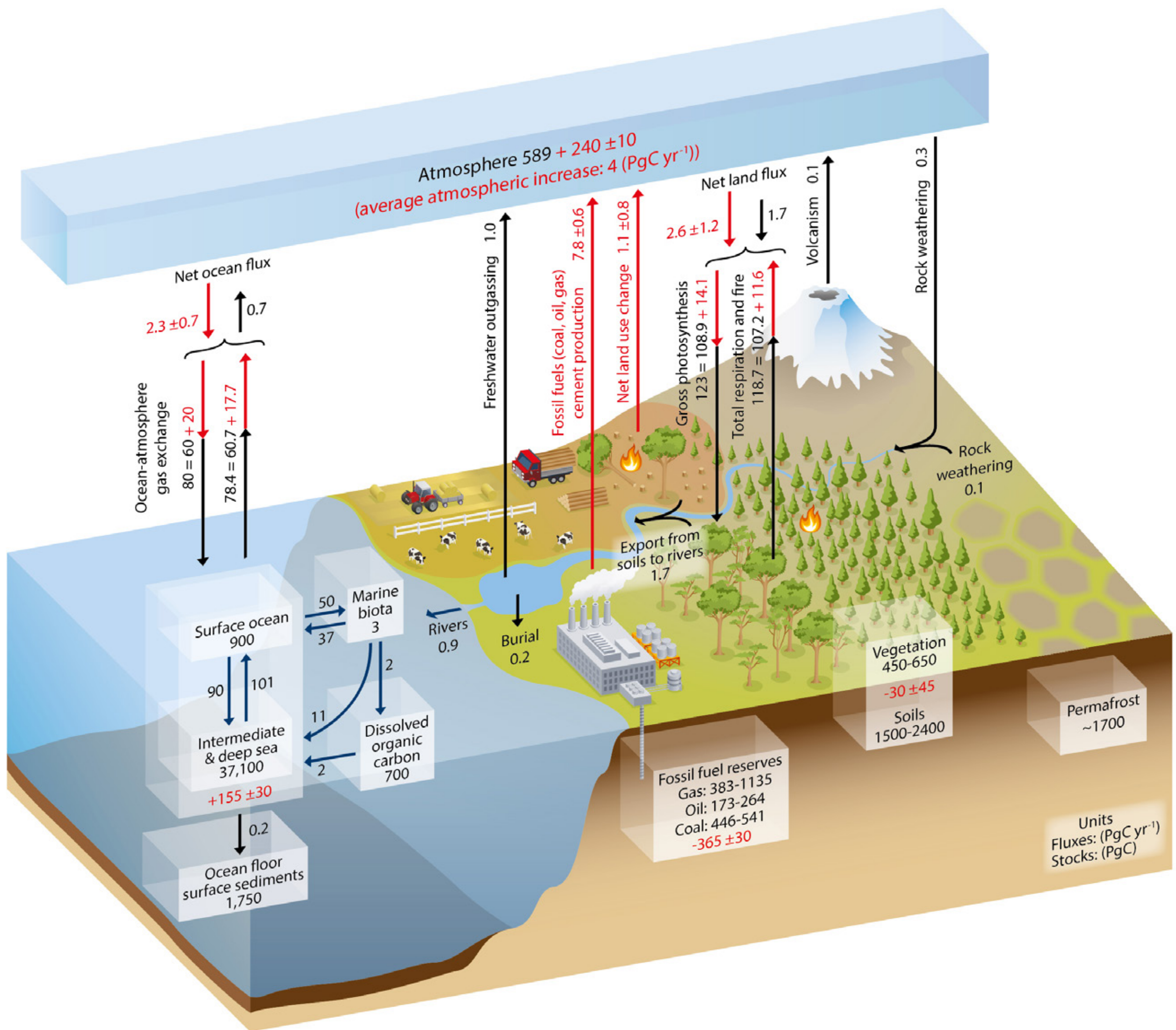


Figure 1.2. A Simplified Pictorial Illustration of the Global Carbon Cycle. The boxed numbers represent reservoir mass or carbon stocks in petagrams of carbon (Pg C). Arrows represent annual exchange (fluxes) in Pg C per year. Black numbers and arrows represent preindustrial reservoir masses and fluxes,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

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

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

1.2.1 Carbon Dioxide

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

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

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

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

Year-to-year variability of the global ocean CO_2 sink was thought to be small, at only about ±0.2 Pg C per year or 9% of annual ocean uptake (Wanninkhof et al., 2013); however, recent work by Landschutzer et al. (2016), based on comprehensive measurements of global ΔpCO_2 of ocean surface water, suggests that substantial decadal and interannual variability can exist. They found that during the 1990s, the global ocean sink was likely to have been significantly smaller than after year 2000 (–0.8 ± 0.5 Pg C per year and –2.0 ± 0.5 Pg C per year, respectively). They proposed 1) that these decadal variations are driven by extratropics and are linked with the atmospheric northern and southern annular modes and 2) that interannual variability is driven by the tropical ocean. The variability of the global land sink is larger, varying by 3 to 4 Pg C per year, and most of this variability likely occurs in the tropics (Baker et al., 2006). This global atmospheric CO_2 interannual variability arises primarily from land sink variability because of the strong anticorrelation between CO_2 and $\delta^{13}C$ (e.g., Alden et al., 2010). Terrestrial net carbon exchange gives rise to significant $\delta^{13}C$ variability, whereas air-sea gas exchange does not. The El Niño Southern Oscillation (ENSO) is thought to be a significant driver of tropical carbon flux variability for both the ocean and terrestrial ecosystems. During the warm phase of ENSO, the ocean takes up more carbon because of reduced upwelling and outgassing from the eastern Tropical Pacific. On land, ENSO is associated with outgassing from the terrestrial biosphere, a phenomenon likely associated with drought and warmer global temperatures. Indeed, the strong ENSO of 2016 pushed measured CO_2 concentrations at Mauna Loa to above 400 ppm, where they have remained (Betts et al., 2016).

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

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

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

1.2.2 Methane

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

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

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

Notes

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

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

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

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

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

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

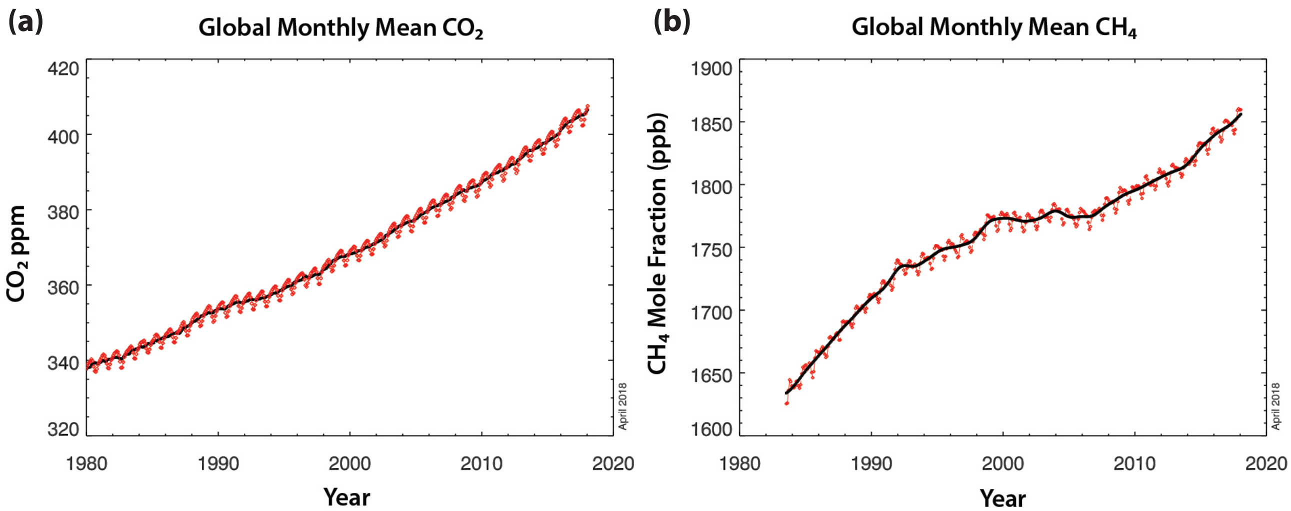


Figure 1.3. Global Averages of Atmospheric Gases Derived from Surface Air Samples. (a) Carbon dioxide (CO_2) in parts per million (ppm). **(b)** Methane (CH_4) in parts per billion (ppb). [Figure source: Redrawn from NOAA-ESRL-GMD 2017.]

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

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

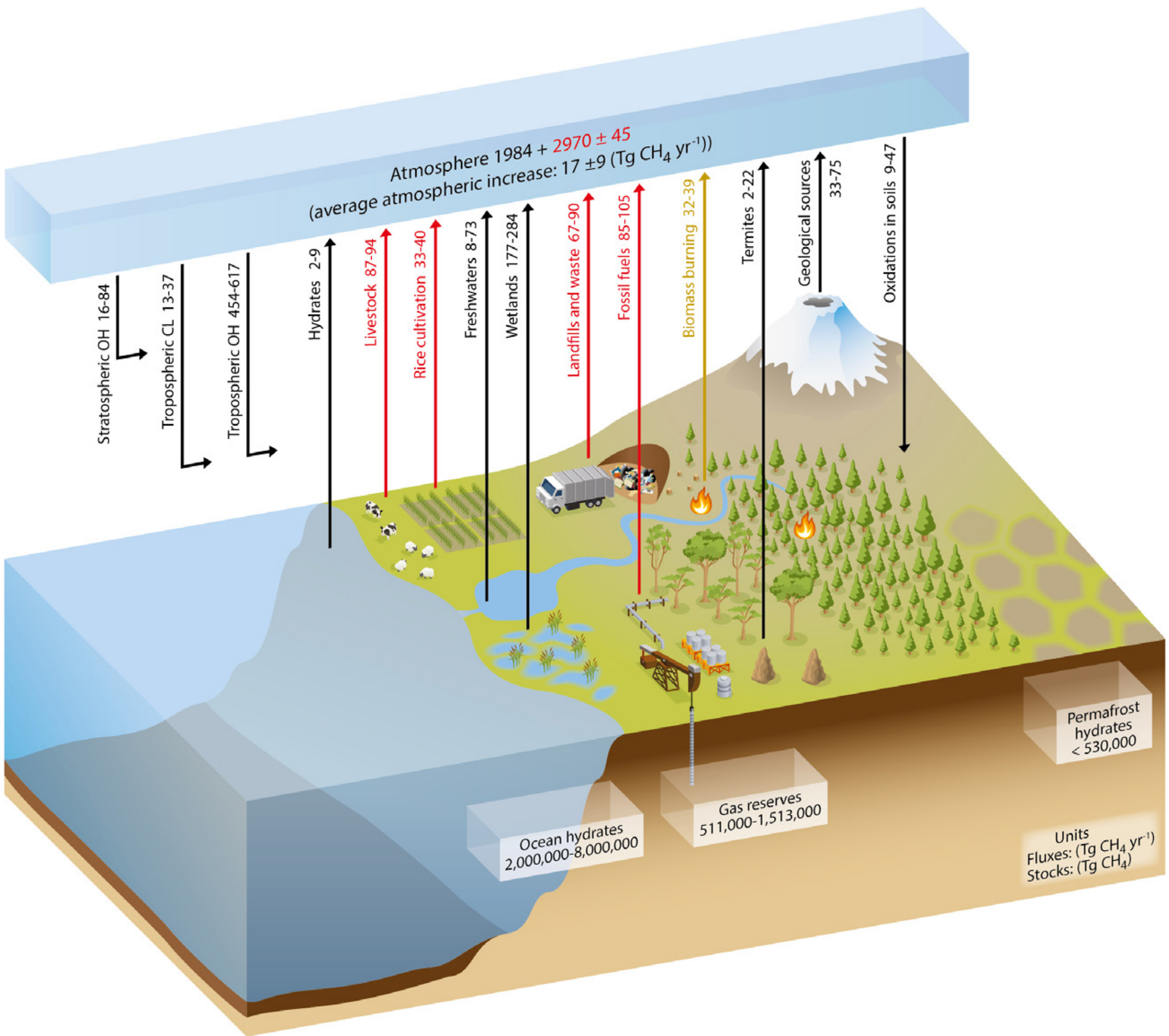
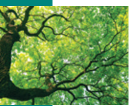


Figure 1.4. A Pictorial Illustration of the Global Methane (CH_4) Cycle. The arrows and boxed numbers represent annual fluxes in teragrams (Tg) of CH_4 per year estimated from 2000 to 2009 and CH_4 reservoirs in Tg CH_4. Reservoirs include the atmosphere and three geological reservoirs (i.e., hydrates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

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



1.3 Perturbations to the Global Carbon Cycle

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

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

1.3.1 Anthropogenic Emissions

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

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

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

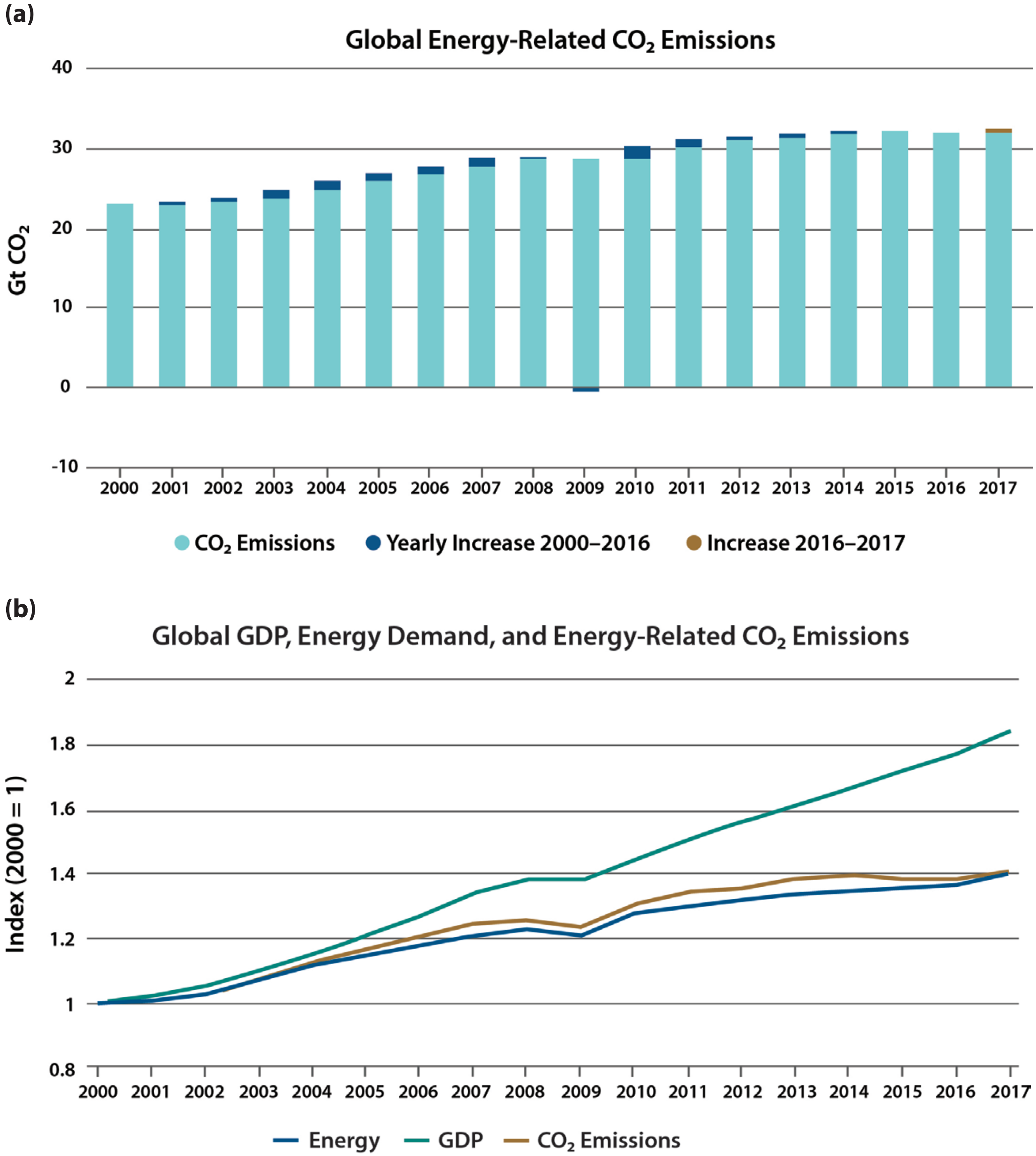

Figure 1.5. Global Energy-Related Carbon Dioxide (CO_2) Emissions. (a) Fossil fuel CO_2 emissions in gigatons (Gt) and their yearly increase. **(b)** Growth in CO_2 emissions, energy demand, and global gross domestic product (GDP) normalized to 2000. [Figure source: Redrawn from International Energy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

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

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

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

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

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

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

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

1.3.2 North American Emissions in a Global Context

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

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

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

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

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

However, the emissions of other GHGs, primarily CH_4 and N_2O, partially offset the potential climate cooling induced by the uptake of CO_2 in North America (Tian et al., 2016). North America accounts for about 10% of natural (e.g., wetlands) and 12% of human-driven (e.g., agriculture and fossil fuels) global CH_4 emissions (Kirschke et al., 2013; see Ch. 2: The North American Carbon Budget).

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

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

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

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

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

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

1.5 The Carbon Cycle and Climate Mitigation

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

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

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

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

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

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

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

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

Another unknown is how much of an overshoot is possible—that is, by how much and for how long emissions could exceed the limit imposed by a 2°C ceiling and their effects still be reversible. Moreover, questions include: How would they be reversed with only limited, available negative emissions? What are the tipping points? For example, warming already is thawing permafrost and thereby exposing long-frozen organic carbon to oxidation. Estimates are that emissions of carbon from thawing permafrost could be 146 to 160 Pg C by 2100 (Schuur et al., 2015), enough to counter negative emissions. Similarly, disruption of tropical and subtropical ecosystems could lead to substantial releases of carbon into the atmosphere. Avoidance of tipping points is a paramount challenge to civilization. Only by continuing to seek a better understanding of the carbon cycle can the predictability of these events be improved.

SUPPORTING EVIDENCE

KEY FINDING 1

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

Description of evidence base

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

Major uncertainties

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

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

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

Summary sentence or paragraph that integrates the above information

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

KEY FINDING 2

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

Description of evidence base

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

Major uncertainties

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

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

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

Summary sentence or paragraph that integrates the above information

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

KEY FINDING 3

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

Description of evidence base

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

Major uncertainties

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

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

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

Summary sentence or paragraph that integrates the above information

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

KEY FINDING 4

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

Description of evidence base

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

Major uncertainties

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

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

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

Summary sentence or paragraph that integrates the above information

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

KEY FINDING 5

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

Description of evidence base

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

Major uncertainties

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

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

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

Summary sentence or paragraph that integrates the above information

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

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2 The North American Carbon Budget

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KEY FINDINGS

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

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

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

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

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

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

2.1 Introduction

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

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

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

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

2.1.1 Approaches for Estimating Carbon Budgets

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

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

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

2.1.2 Carbon Cycling Synthesis Efforts

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

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

2.1.3 Chapter Objectives

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

2.2 Historical Context

2.2.1 Continental Net Carbon Source

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

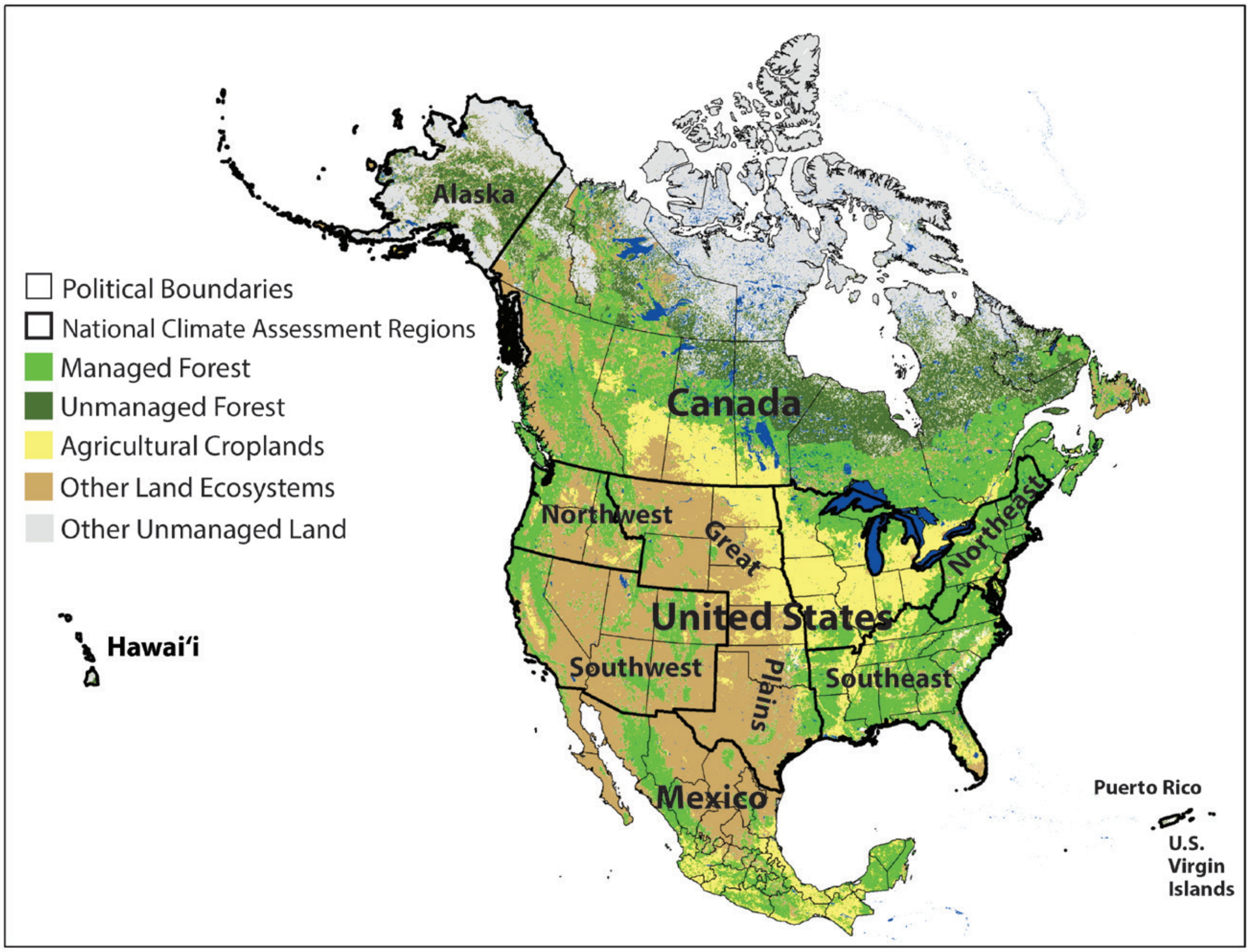

Figure 2.1. Spatial Domain of the Carbon Budget Synthesis for North America. Broadly represented in this map are the general carbon cycle sectors of forests, agriculture, other lands, and coastal regions intersected by the national boundaries of Canada, the United States, and Mexico. [Data source: Sector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

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

2.2.2 Continental Land and Coastal Ocean Sinks

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

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

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

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

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

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

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

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

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

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

2.3 Current Understanding of Carbon Stocks and Fluxes

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

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

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

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

Notes

a) Data, in teragrams of carbon (Tg C), are from the sector-based chapters of this report.
b) Includes above- and belowground biomass plus deadwood (Table 9.2, p. 368).
c) Includes litter plus soil (Table 9.2).
d) Canadian estimate (Table 12.4, p. 483); U.S estimate from Rapid Carbon Assessment (RaCA) project (Table 12.1,p. 479); Mexican grazing lands estimate (Table 12.3, p. 482).
e) Estimate for conterminous United States only (Table 10.2, p. 403).
f) ND = no data; NA = not applicable.
g) Conterminous U.S. estimate (Table 10.2); Mexican estimate for "Other Lands" (Table 12.2, p. 481).
h) Tundra vegetation biomass for Canada and Alaska (Table 11.2, p. 442).
i) North America contains about one-third of the total estimated 1,460 to 1,600 petagrams of carbon (Pg C) stock of circumpolar permafrost soils (to a 3-m depth; see Ch. 11: Arctic and Boreal Carbon, p. 428).
j) Calculated as 2% of the total carbon stock of nonforested wetlands with peatland and mineral soils (Table 13.1, p. 514).
k) Calculated as 98% of the total carbon stock of nonforested wetlands with peatland and mineral soils (Table 13.1).
l) The total estimated carbon stocks from tidal wetlands, estuaries, and seagrasses (see Ch. 15: Tidal Wetlands and Estuaries, p. 596.

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

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

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

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

Notes

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

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

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

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

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

2.3.1 Fossil Fuel Emissions

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

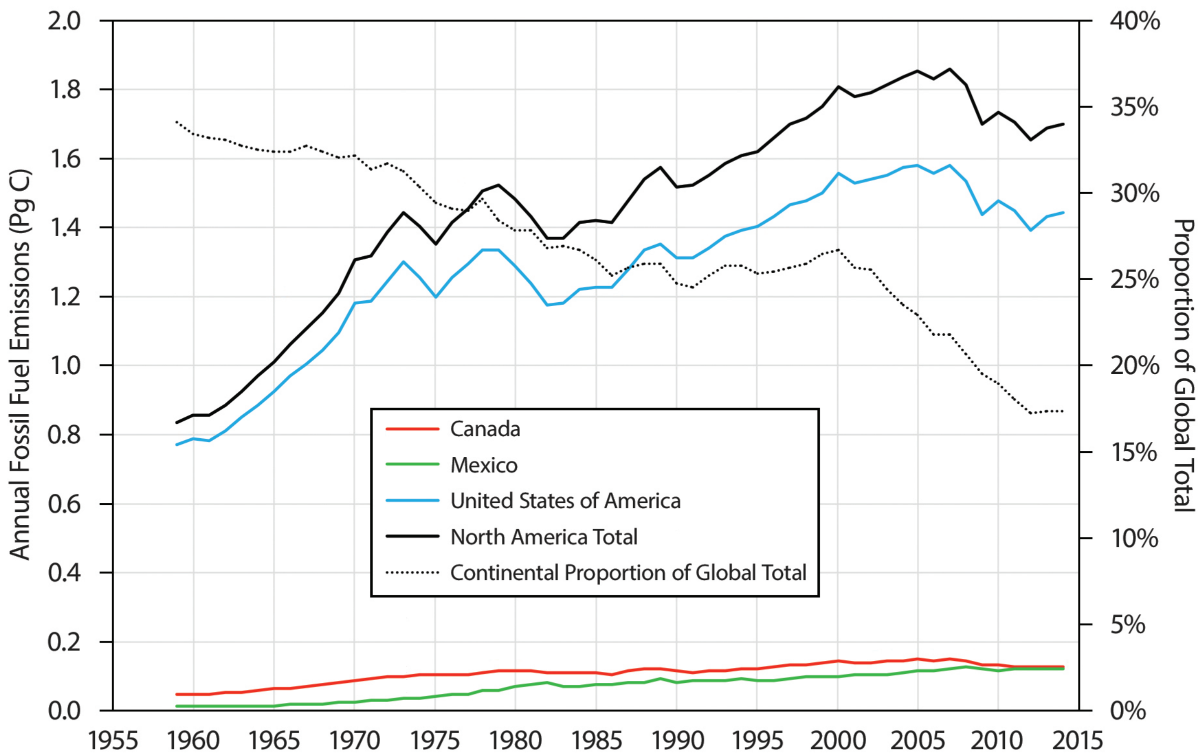

Figure 2.2. Annual North American Fossil Fuel Emissions from 1959 to 2014. Emissions values are given in petagrams of carbon (Pg C) for each country and for the continent as a whole (solid lines, left vertical axis). The dotted line shows the North American proportion of total global emissions (right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

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

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

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

2.3.2 Net Ecosystem Exchange

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

2.3.3 Stock Changes, Emissions, and Lateral Transfers of Carbon

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

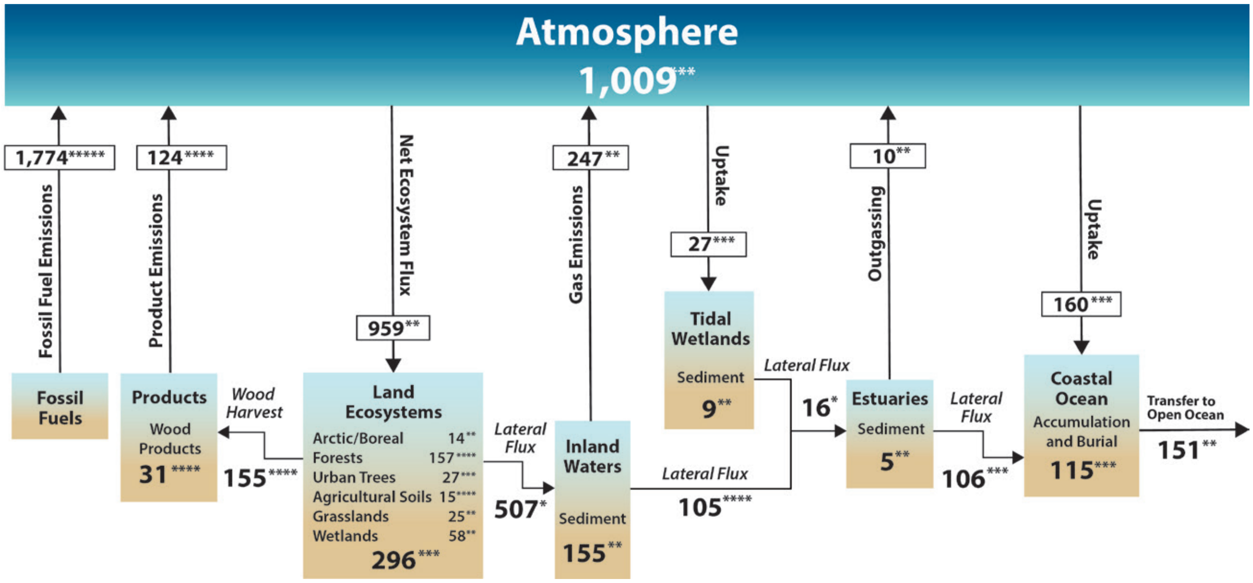

Figure 2.3. Major Components of the North American Carbon Cycle. For each component, estimates are shown for average annual stock changes (boxes), fluxes (vertical arrows), and lateral transfers (horizontal arrows) from ca. 2004 to 2013, the approximately 10-year period since the *First State of the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

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

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

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

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

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

2.3.4 Determining Coastal Ocean and Methane Impacts

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

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

2.4 Trends in North American Carbon Cycling

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

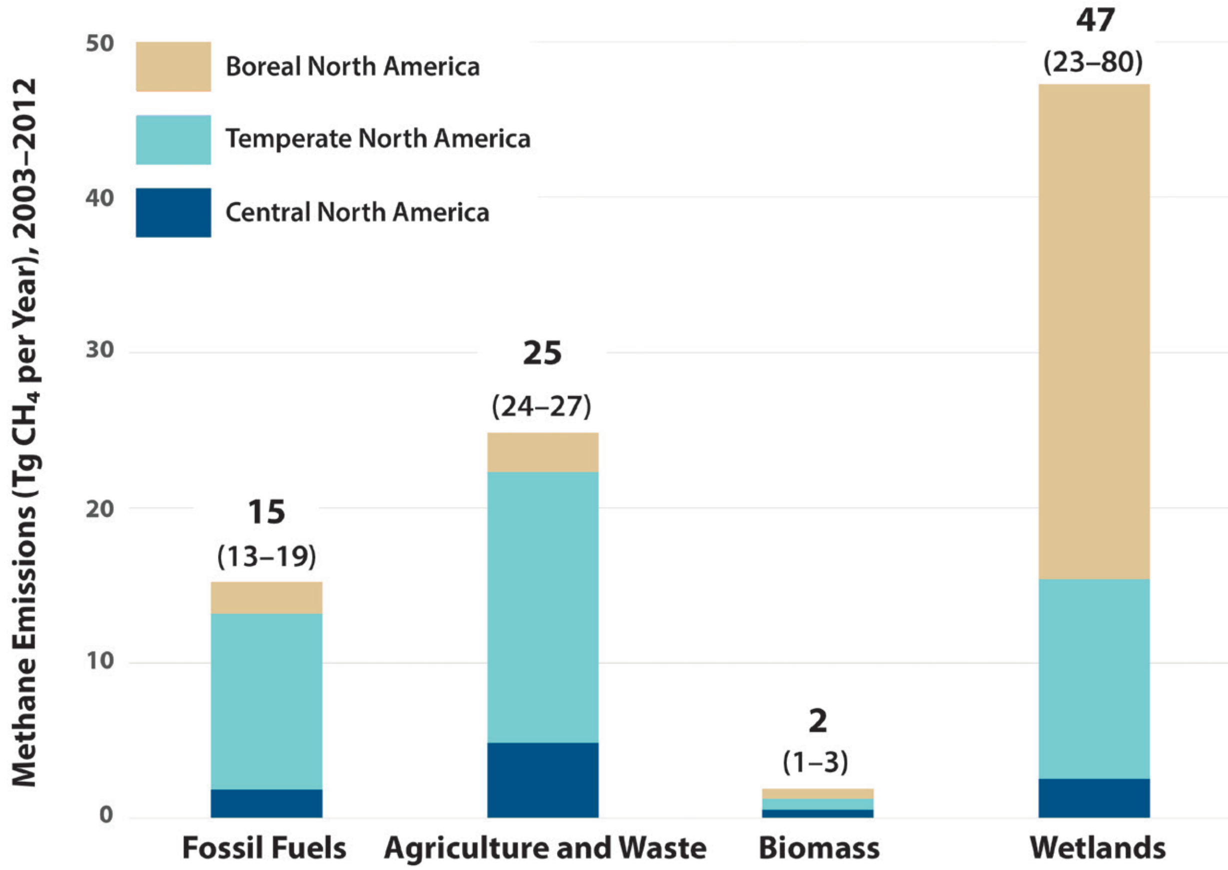

Figure 2.4. Sources of Methane (CH_4) Emissions Estimated from Bottom-Up Methods for Three Regions of North America from 2003 to 2012. The Boreal North America region includes Canada and Alaska; Temperate North America represents the conterminous United States; and Central North America includes Mexico,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

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

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

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

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

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

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

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

2.5 Regional Context

2.5.1 Canada, the United States, and Mexico

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

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

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

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

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

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

2.5.2 National Climate Assessment Regions of the United States

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

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

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

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

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

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

2.6 Societal Drivers, Impacts, and Carbon Management

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

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

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

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

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

2.7 Synthesis, Knowledge Gaps, and Outlook

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

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

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

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

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

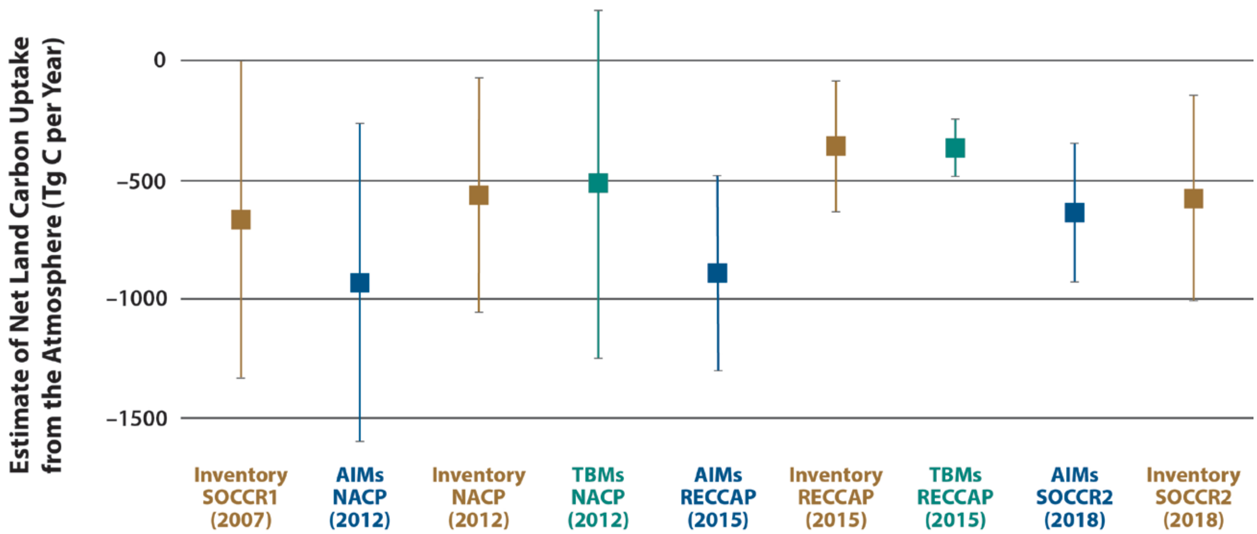

Figure 2.5. Estimates of the North American Carbon Sink in this Century. These estimates, in teragrams of carbon (Tg C) per year, are derived from inventory analysis, atmospheric inversion models (AIMs), and terrestrial biosphere models (TBMs). [Data sources: *First State of the Carbon Cycle Report*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

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

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

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

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

SUPPORTING EVIDENCE

KEY FINDING 1

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

Description of evidence base

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

Major uncertainties

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

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

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

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

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

Summary sentence or paragraph that integrates the above information

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

KEY FINDING 2

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

Description of evidence base

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

Major uncertainties

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

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

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

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

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

Summary sentence or paragraph that integrates the above information

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

KEY FINDING 3

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

Description of evidence base

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

Major uncertainties

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

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

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

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

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

Summary sentence or paragraph that integrates the above information

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

KEY FINDING 4

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

Description of evidence base

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

Major uncertainties

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

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

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

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

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

Summary sentence or paragraph that integrates the above information

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

KEY FINDING 5

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

Description of evidence base

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

Major uncertainties

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

Summary sentence or paragraph that integrates the above information

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

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