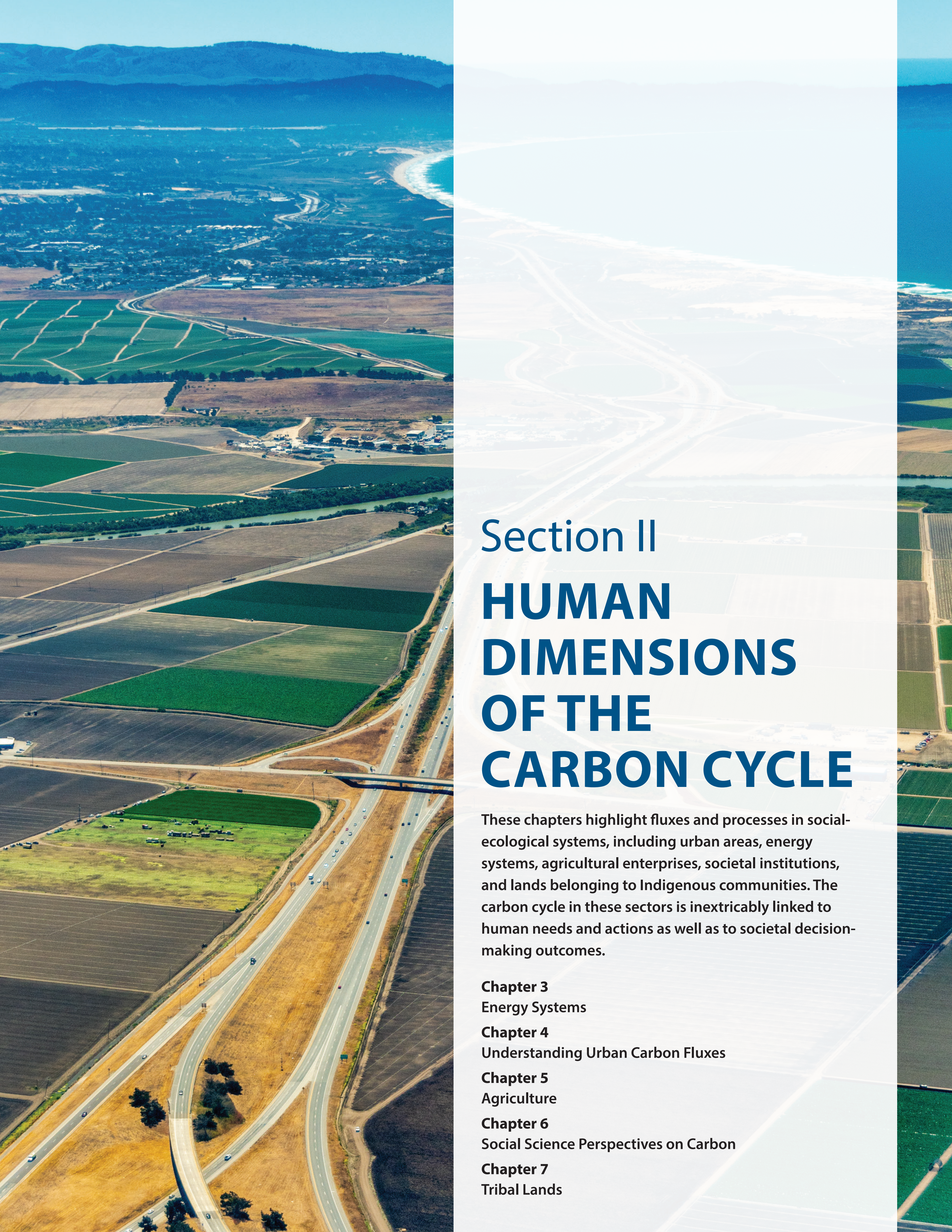

Section II

HUMAN DIMENSIONS OF THE CARBON CYCLE

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

3 Energy Systems

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KEY FINDINGS

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

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

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

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

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

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

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

3.1 Introduction

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

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

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

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

3.2 Historical Context

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

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

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

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

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

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

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

3.3 North American Energy System

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

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

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

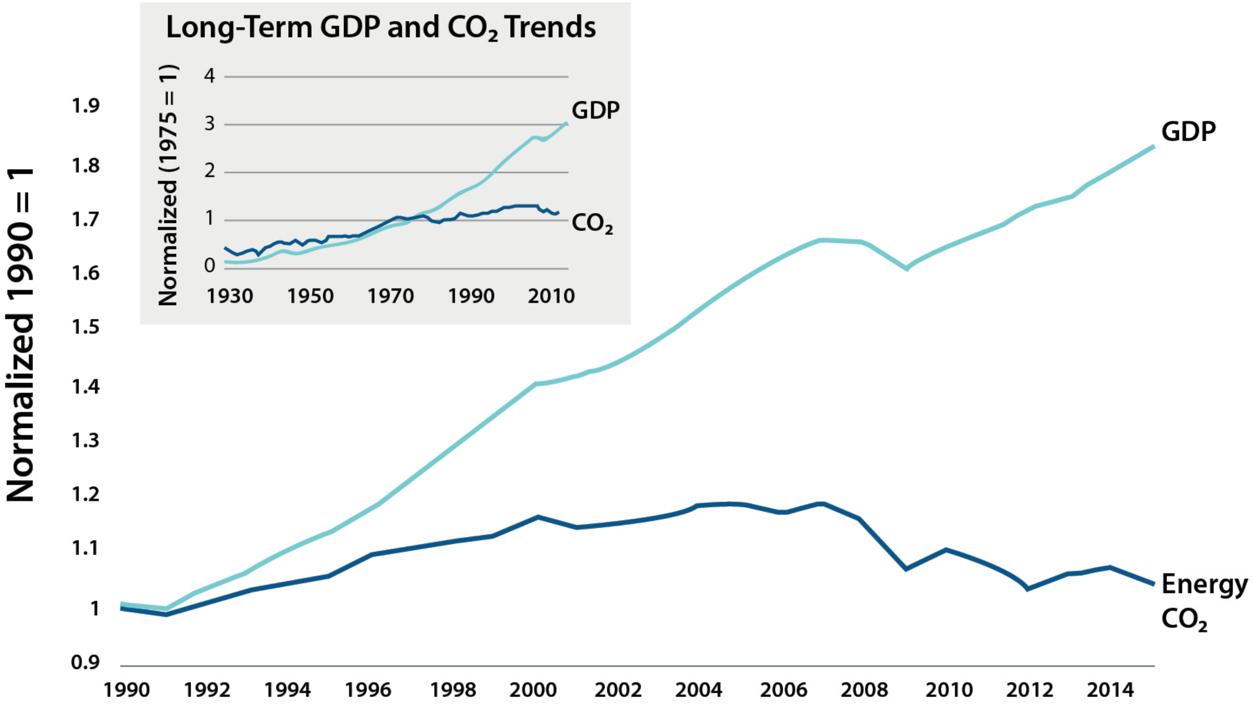

Figure 3.1. U.S. Energy Carbon Dioxide (CO_2) Emissions and Gross Domestic Product (GDP).

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

3.3.1 Size of the North American Energy System

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

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

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

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

Notes

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

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

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

The continent's proven oil reserves amounted to 1.5 ZJ in 2011, or more than 12% of the global total in 2015. Canada's oil reserves, the largest in North America, are the third largest in the world after Saudi Arabia and Venezuela. Particularly significant to the carbon cycle are Alberta's oil sands, which underlie 142,000 km^2 of land in the Athabasca, Cold Lake, and Peace River areas in the northern part of the province. Mining and processing this unconventional source of oil currently account for approximately 8.5% of Canada's total CO$_2$e emissions (Government of Alberta [Canada] 2016). Oil sands also now represent about 98% of Canada's growing oil reserves and about half the country's production in 2011. Despite this large reserve, in 2015 the United States produced 23.7 EJ, more than twice as much as Canada's production of 9.04 EJ. The United States also has developed unconventional technologies for extracting oil, including from shales. Proven oil reserves in the United States increased by 57% from 2005 to 2015 (EIA 2016k), and by 2012 shale oil accounted for about 22% of those reserves (EIA 2014a). Mexico's oil reserves have decreased over the past decades. Although the country's Cantarell oil field is one of the largest in the world, production has declined since 2003. In 2011, Mexico's oil reserves were 62.8 EJ. According to BP (2016), oil reserves within the country have fallen from 285 EJ in 1995. Mexican oil production has been relatively stagnant since 2009 (World Energy Council 2016a). Overall, the North American share of total global proven oil reserves was 14% in 2016, with a projected use of more than 32 years of reserves under current conditions (BP 2017b).

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

Box 3.1 Energy Resources and Reserves

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

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

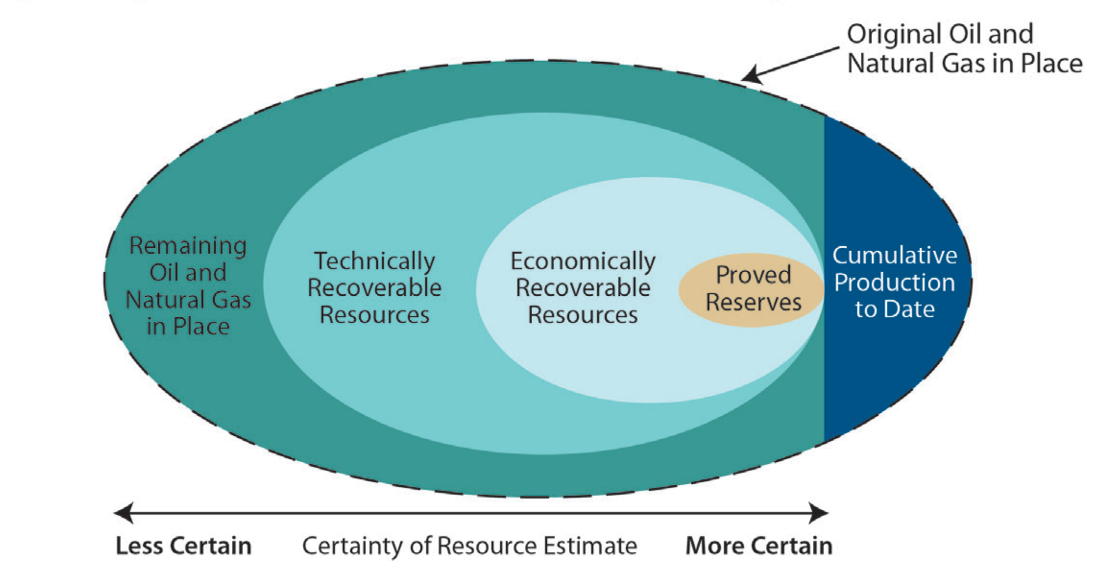

Figure 3.2. Stylized Representation of Oil and Natural Gas Resource Categories. Figure is not to scale. [Figure source: Redrawn from EIA 2014b.]

Continued on next page

(Continued)

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

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

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

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

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

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

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

Notes

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

b) GW, gigawatts.

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

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

3.3.2 North American Subsystem Contributions to Carbon Emissions

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

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

Electricity

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

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

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

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

Box 3.2 Potential for Nuclear Power in North America

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

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

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

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

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

Continued on next page

(Continued)

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

Residential and Commercial Buildings

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

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

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

Alternatively, removing electricity-related emissions from the buildings sector makes the sector's share of CO$_2$e emissions across the region the lowest among end-use sectors. For example, in 2013, the U.S. commercial and residential sectors together accounted for 10% of total national CO$_2$e emissions (U.S. EPA 2016; see Figure 3.3, p. 125). The U.S. commercial sector emitted approximately 59 Tg C, and the residential sector was responsible for about 89.5 Tg C. The Canadian buildings sector emitted 74 Tg CO$_2$e (20.2 Tg C), or 10% of total national emissions (ECCC 2016b). In Mexico, the buildings sector emitted about 25.6 Tg CO$_2$e (7.0 Tg C) in 2013, representing about 5% of total net national emissions for that year (SEMARNAT-INECC 2016).

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

Industry

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

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

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

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

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

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

Transportation

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

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

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

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

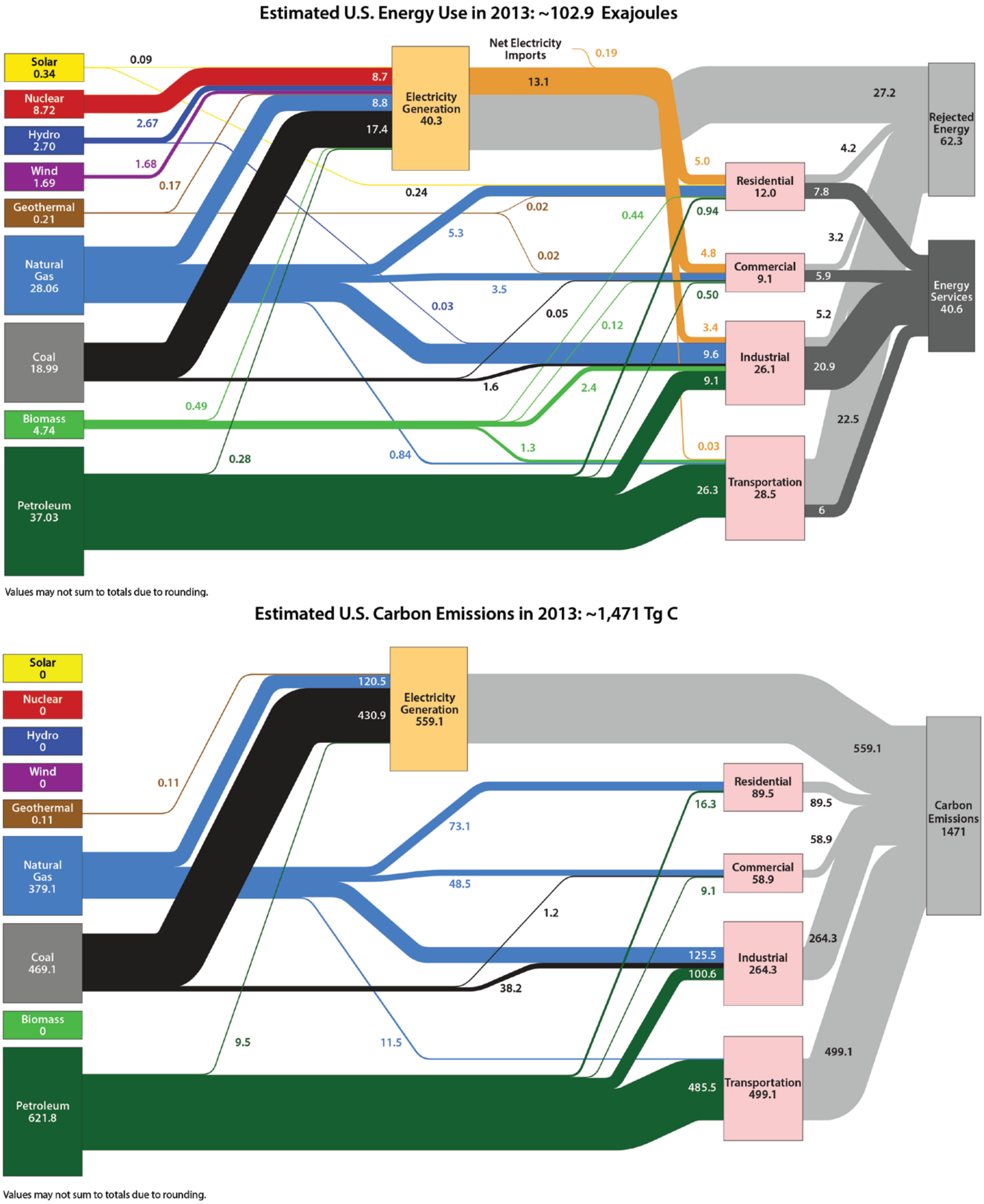
According to IEA (2017a), total North American energy use for transportation exceeded 30 EJ in 2013. The U.S. transportation sector consumed around 28.5 EJ of this energy, 91.6% of which was from petroleum, 3.3% from natural gas, and 5.0% from biofuels (EIA 2017b; IEA 2016d). Canada's transportation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

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

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

Summary

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



Estimated U.S. Energy Use in 2013: ~102.9 Exajoules

Values may not sum to totals due to rounding.

Estimated U.S. Carbon Emissions in 2013: ~1,471 Tg C

Values may not sum to totals due to rounding.

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

3.3.3 Carbon Sink Technologies

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

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

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

3.4 Indicators, Trends, and Feedbacks

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

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

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

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

Notes

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

3.4.1 Decline in Energy Use and CO_2e Emissions

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

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

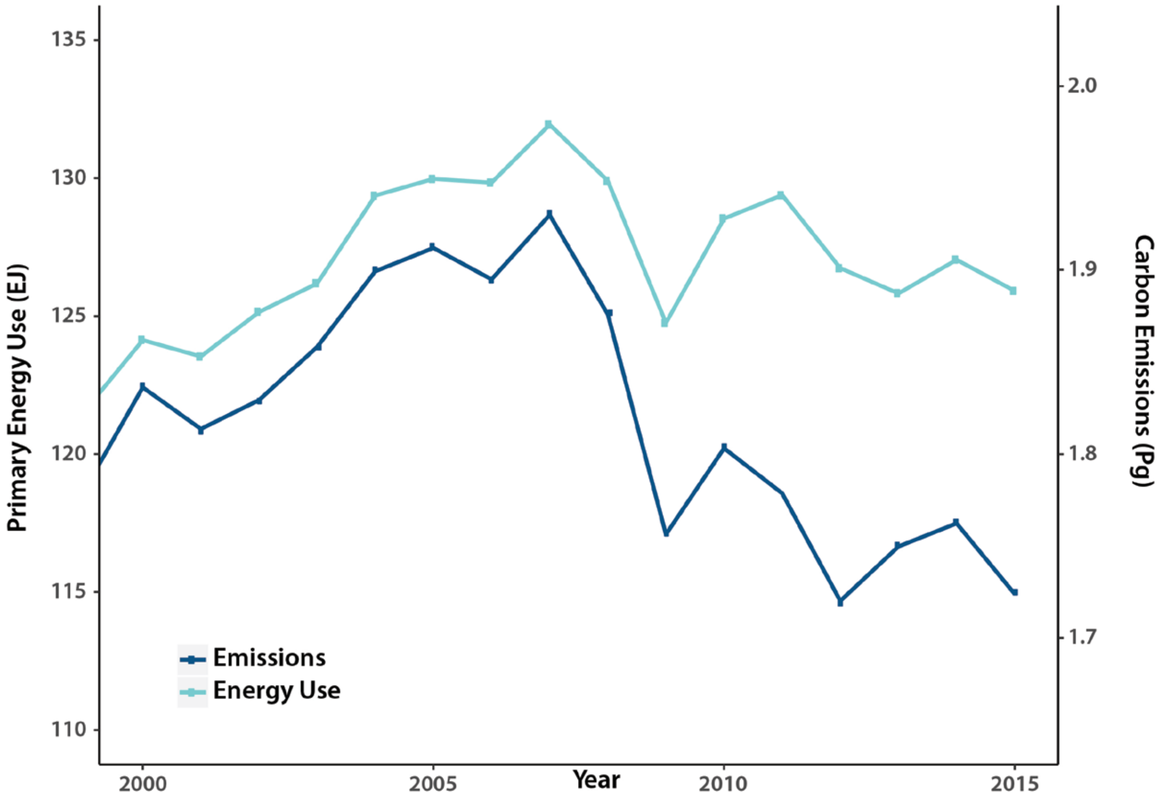


Figure 3.4. North American Primary Energy Consumption and Carbon Emissions, 2000 to 2015. Energy use in exajoules (EJ); carbon emissions in petagrams (Pg). [Data source: EIA 2017i.]

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

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

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

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

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

3.4.2 North American Natural Gas Energy Transition

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

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

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

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

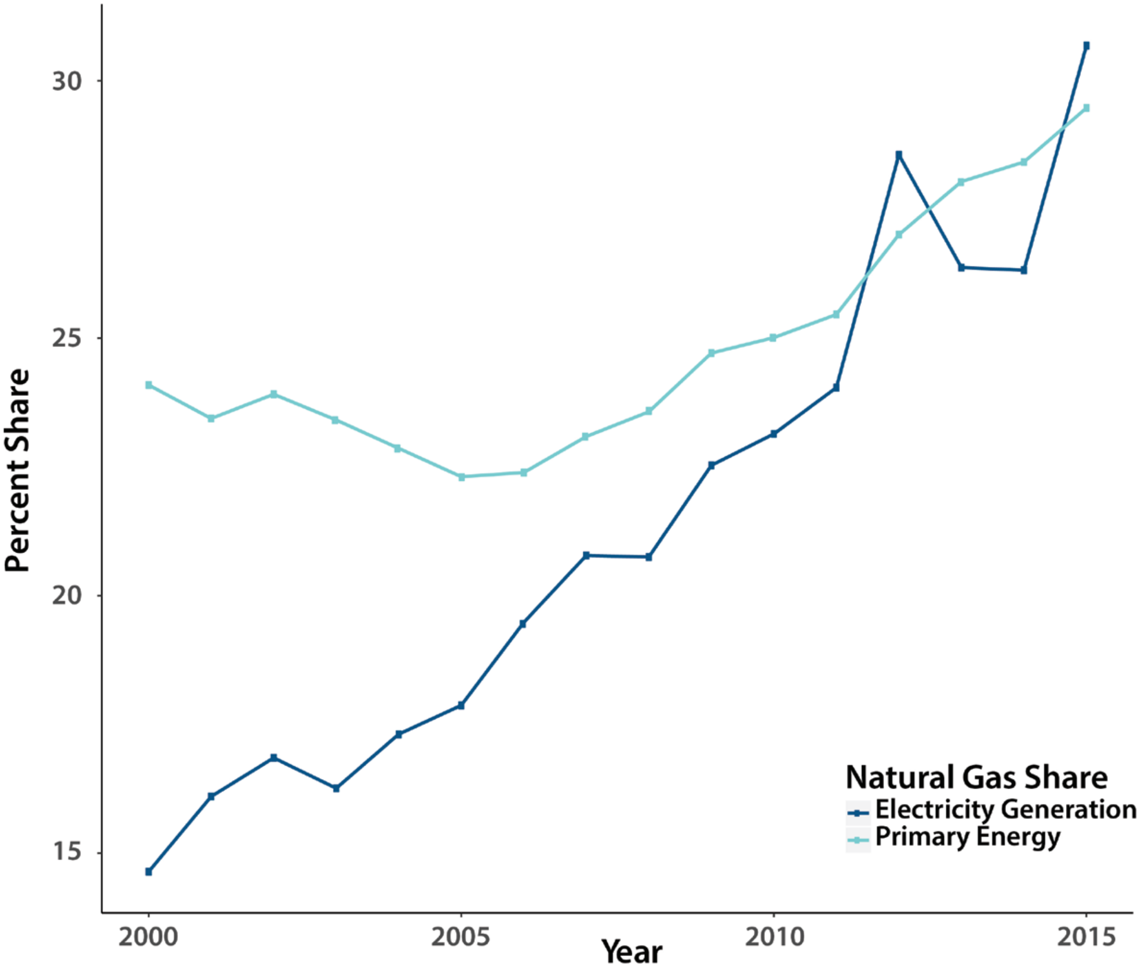


Figure 3.5. North American Natural Gas Share of Primary Energy and Electricity Generation, 2000 to 2015. [Data sources: EIA 2017i and IEA 2017b]

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

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

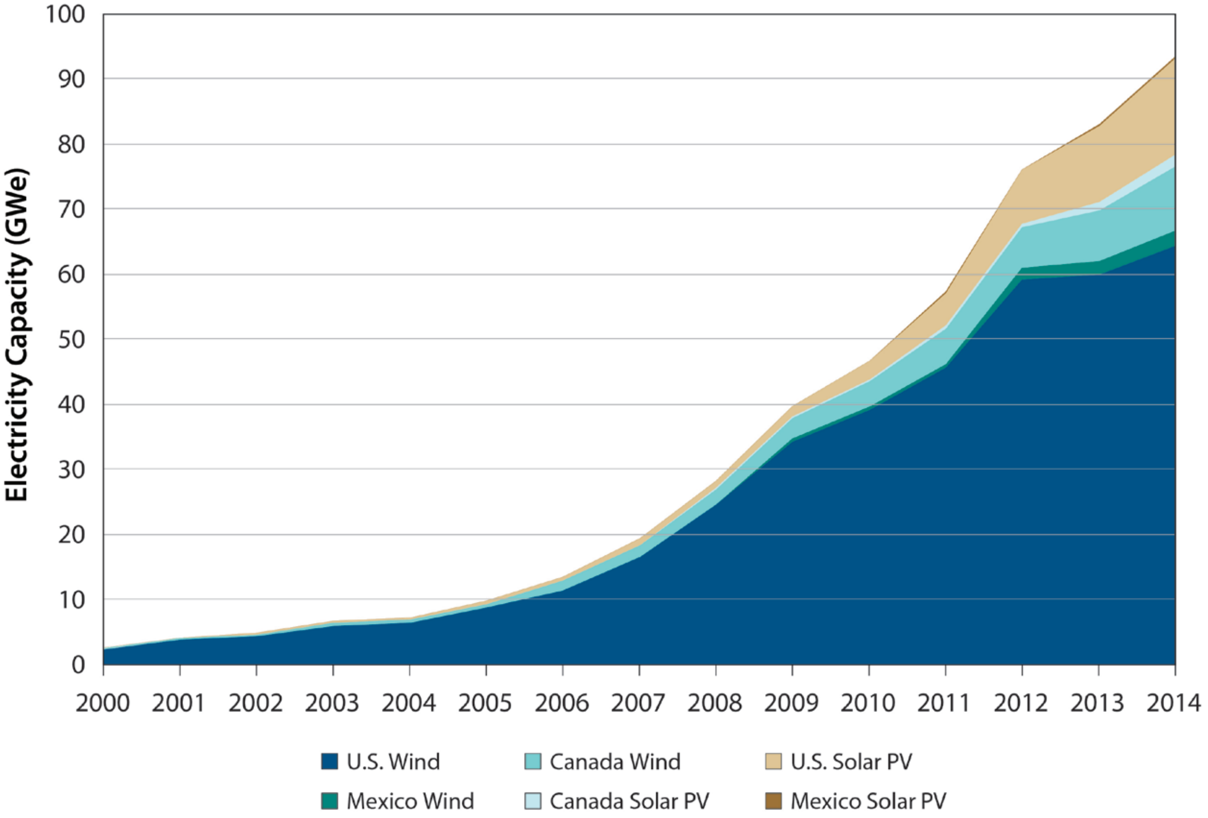


Figure 3.6. North American Wind and Solar Net Capacity, 2000 to 2014. Key: GWe, gigawatt electrical; PV, photovoltaic. [Data source: IEA 2018.]

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

3.4.3 Increase in Renewable Energy

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

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

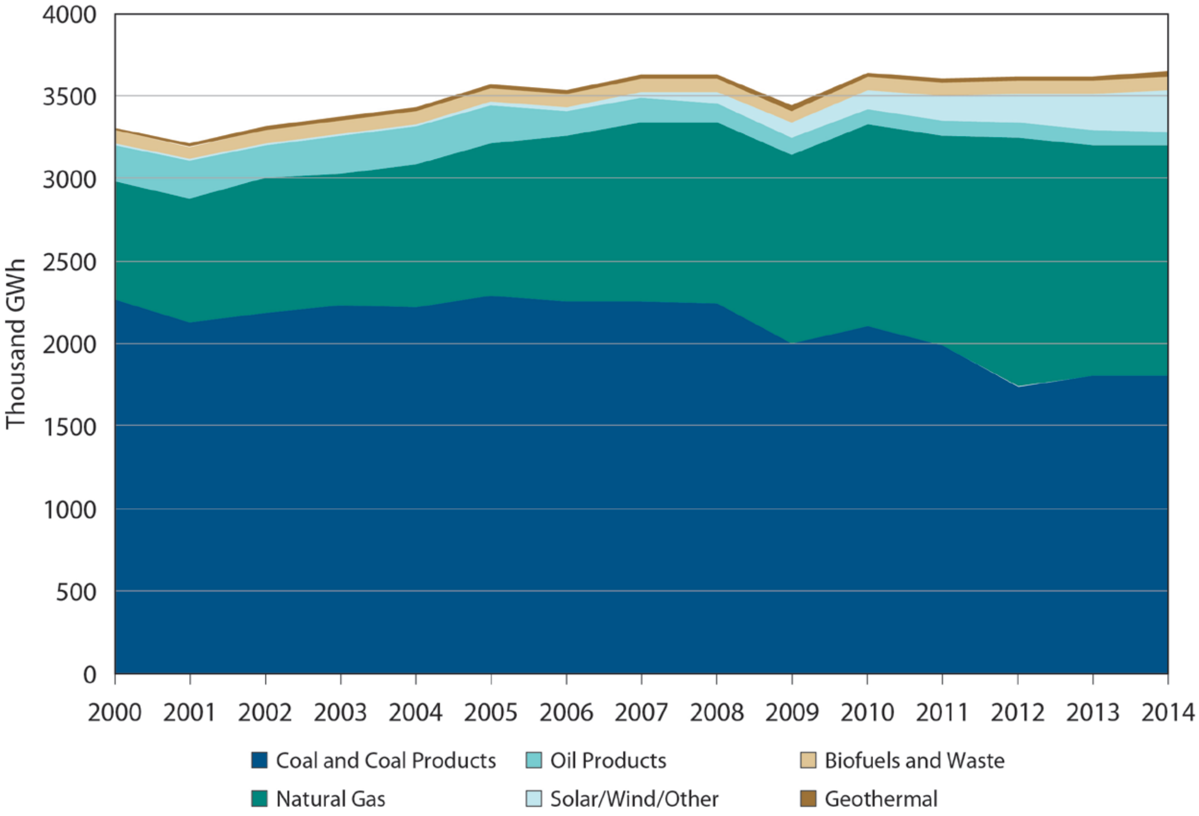


Figure 3.7. Renewable and Fossil Fuel Electricity Production in North America, 2000 to 2014. Key: GWh, gigawatt hours. [Data source: IEA 2017a.]

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

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

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

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

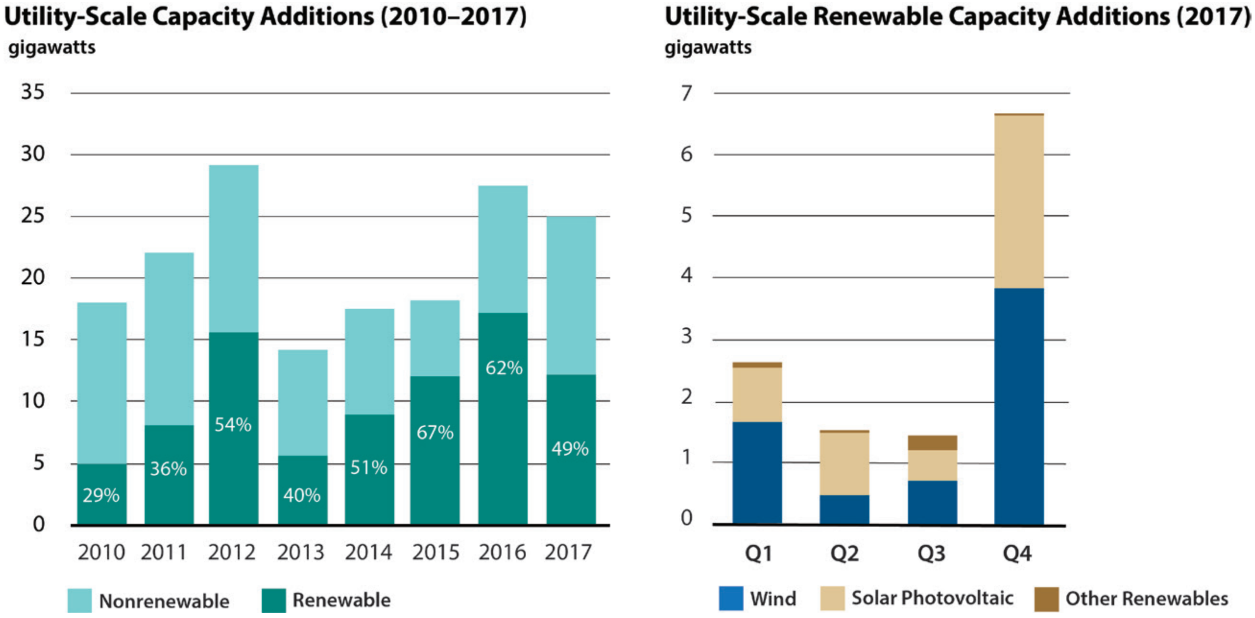

Figure 3.8. Renewable Generation Capacity (2010 to 2017) and Utility-Scale Additions, 2017. [Figure source: Redrawn from EIA 2018b.]

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

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

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

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

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

3.4.4 Growing Concern over Aging Energy Infrastructure

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

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

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

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

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

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

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

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

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

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

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

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

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

Box 3.3 Methane Emissions from Oil and Gas Production

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

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

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

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

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

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

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

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

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

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

3.4.6 Feedbacks

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

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

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

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

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

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

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

3.5 Global, North American, and Regional Context

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

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

3.6 Societal Drivers and Impacts

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

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

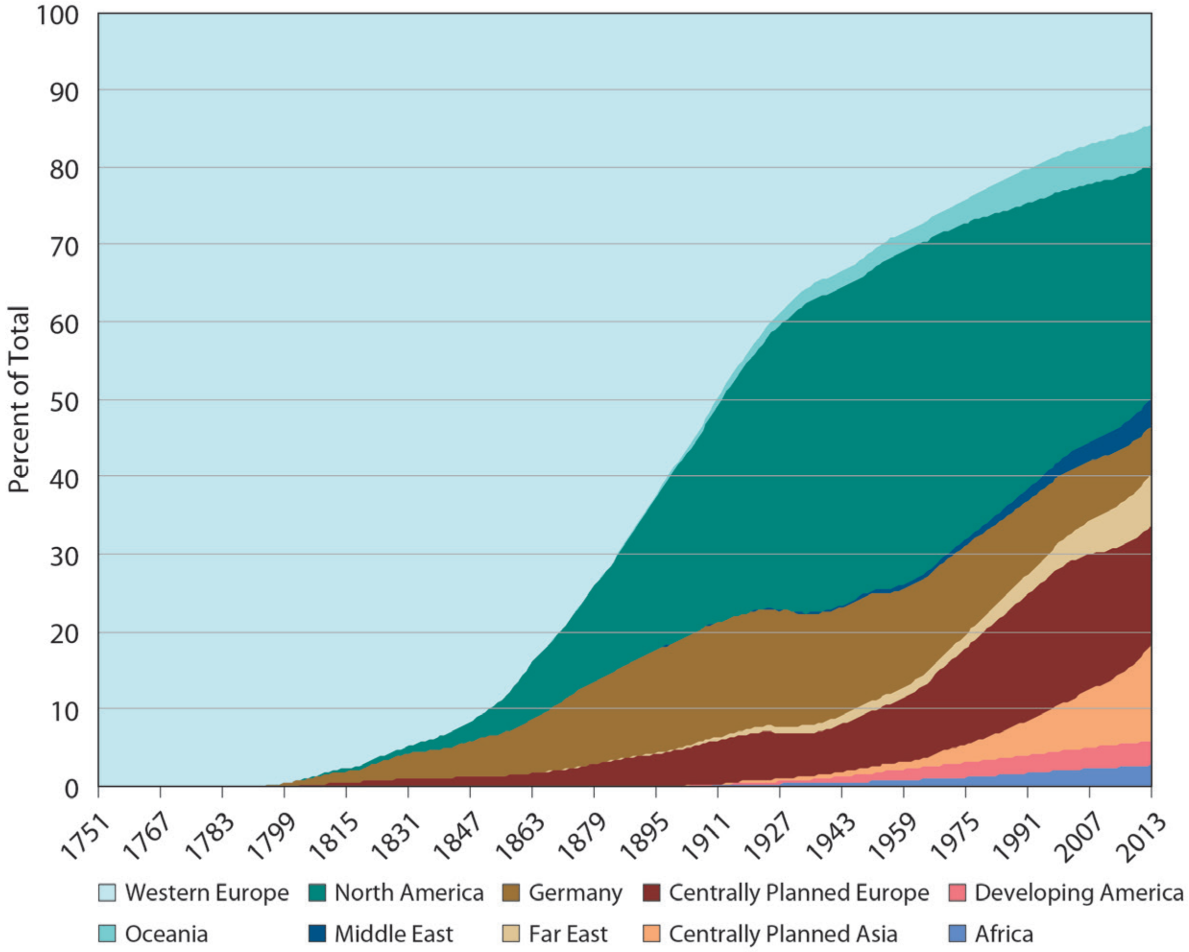

Figure 3.9. Change in Cumulative Share of Carbon Dioxide Emissions from Fossil Fuel Burning, Cement Manufacture, and Gas Flaring. Percentages are by region, from 1751 to 2013. [Data source: Boden et al., 2016.]

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

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

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

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

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

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

3.6.1 Population Growth

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

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

3.6.2 Financial Crisis and Declines in GDP Growth

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

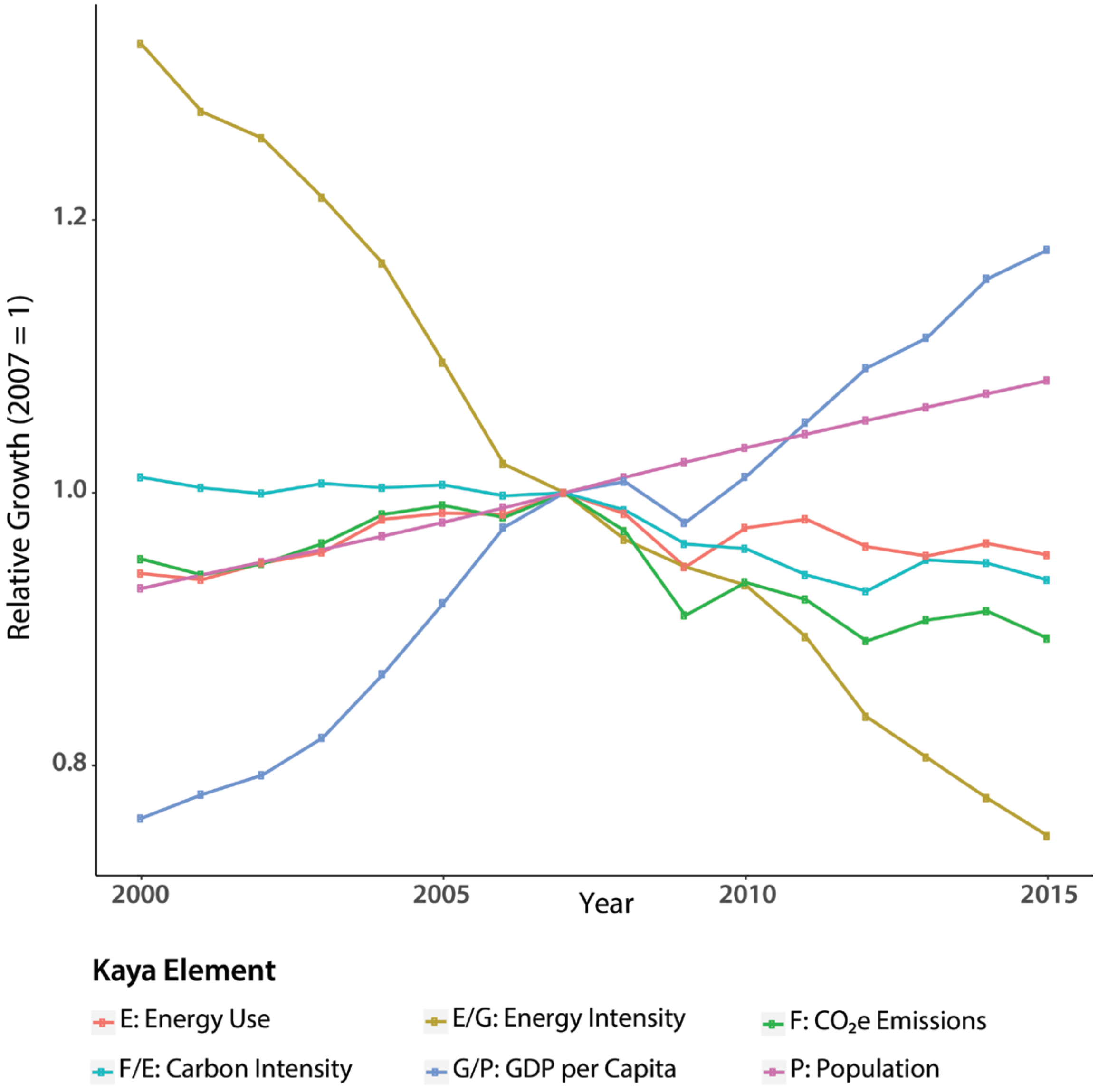

Figure 3.10. Kaya Identity Decomposition, 2000 to 2015. Key: CO_2e, carbon dioxide equivalent; GDP, gross domestic product. [Data sources: EIA 2017i and World Bank 2017.]

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

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

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

3.6.3 Reduced Energy Intensity

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

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

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

Table 3.4. LEED-Certified Buildings and Gross m^2 Coverage in North America (2016)[a,b]

Area	Certified		Registered		Grand Total	
	Number	m^2 (millions)	Number	m^2 (millions)	Number	m^2 (millions)
Canada	399	3.97	218	5.01	617	8.98
Mexico	172	2.46	496	11.83	668	14.29
United States	24,777	299.28	31,212	447.26	55,989	746.54
North America	25,348	305.71	31,926	464.10	57,274	769.81

Notes

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

b) LEED, Leadership in Energy and Environmental Design.

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

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

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

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

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

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

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

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

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

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

3.6.4 Decreasing Carbon Intensity

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

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

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

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

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

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

- The natural gas boom, including the shift from coal to cheaper and cleaner natural gas for electricity production and industrial processes (EIA 2017j), with the critically important caveat that venting, flaring, and fugitive emissions may be underestimated (see Section 3.4.2, p. 129, and Box 3.3, p. 137).

- Increased renewables in the fuel mix in all North American countries, including wind, solar, and bioenergy (with caveats mentioned for this last source; see Sections 3.4.3, p. 131, and 3.4.5, p. 135), driven, in part, by declining costs and changing fuel prices.

- A wide range of new technologies including grid-scale electricity storage and alternative fuel vehicles.

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

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

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

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

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

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

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

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

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

3.7 Carbon Management Decisions

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

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

3.7.1 International Carbon Management Decisions and National Responses

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

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

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

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

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

3.7.2 National Energy and Carbon Management Decisions

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

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

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

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

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

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

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

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

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

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

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

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

3.7.3 Subnational Energy and Carbon Management Decisions

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

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

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

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

3.8 Future Outlook

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

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

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

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

3.8.1 Energy and Carbon Emissions Forecasts

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

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

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

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

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

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

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

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

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

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

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

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

3.8.2 Exploratory Energy and Carbon Emissions Scenarios

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

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

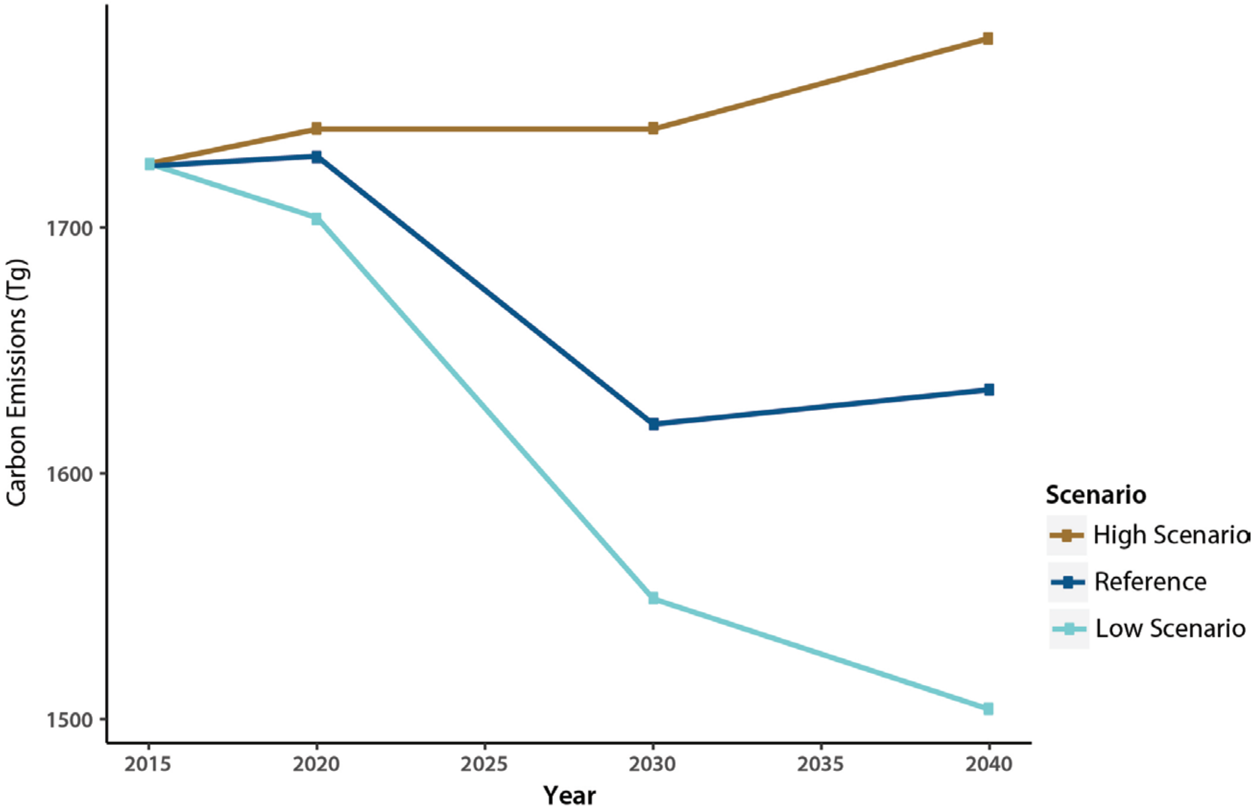

Figure 3.11. North American Energy System Carbon Emissions Scenarios in Teragrams (Tg). [Data sources: EEEC 2016c; EIA 2017k; and IEA 2016b.]

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

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

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

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

Notes

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

b) Tg C, teragrams of carbon.

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

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

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

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

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

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

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

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

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

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

Notes

a) Source: Clarke et al., 2014.

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

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

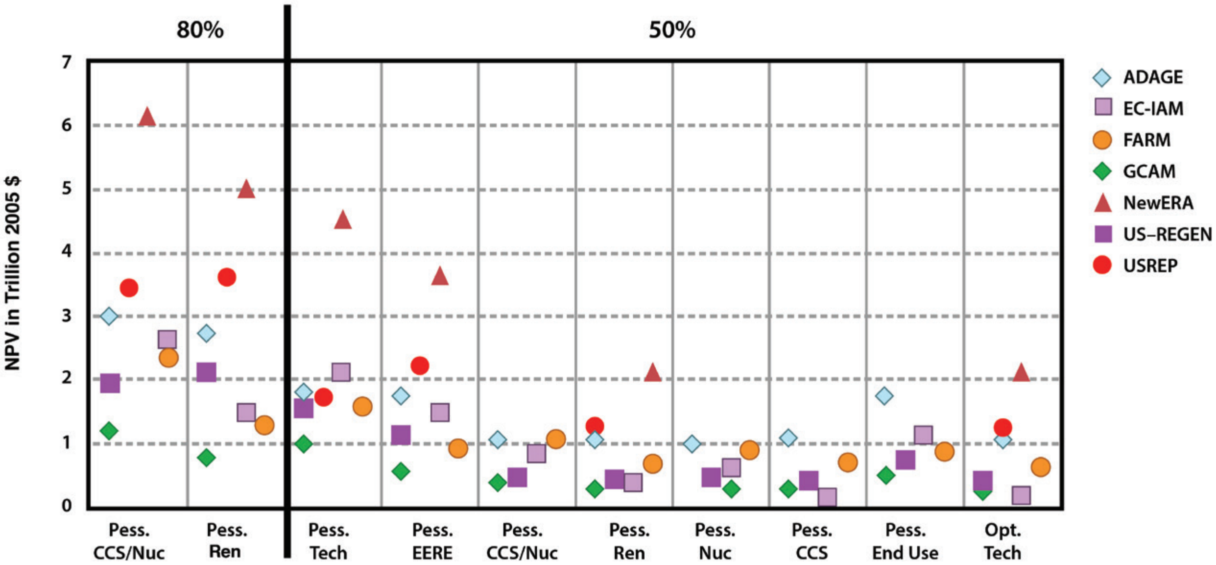

Figure 3.12. Net Present Value of Mitigation Costs from 2010 to 2050 from Seven Different Models. The measures presented are the total mitigation costs for 50% and 80% reductions in carbon emissions. Results suggest that total mitigation costs across pessimistic and optimistic technology assumptions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

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

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

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

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

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

3.8.3 Energy and Carbon Emissions Backcasting Scenarios

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

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

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

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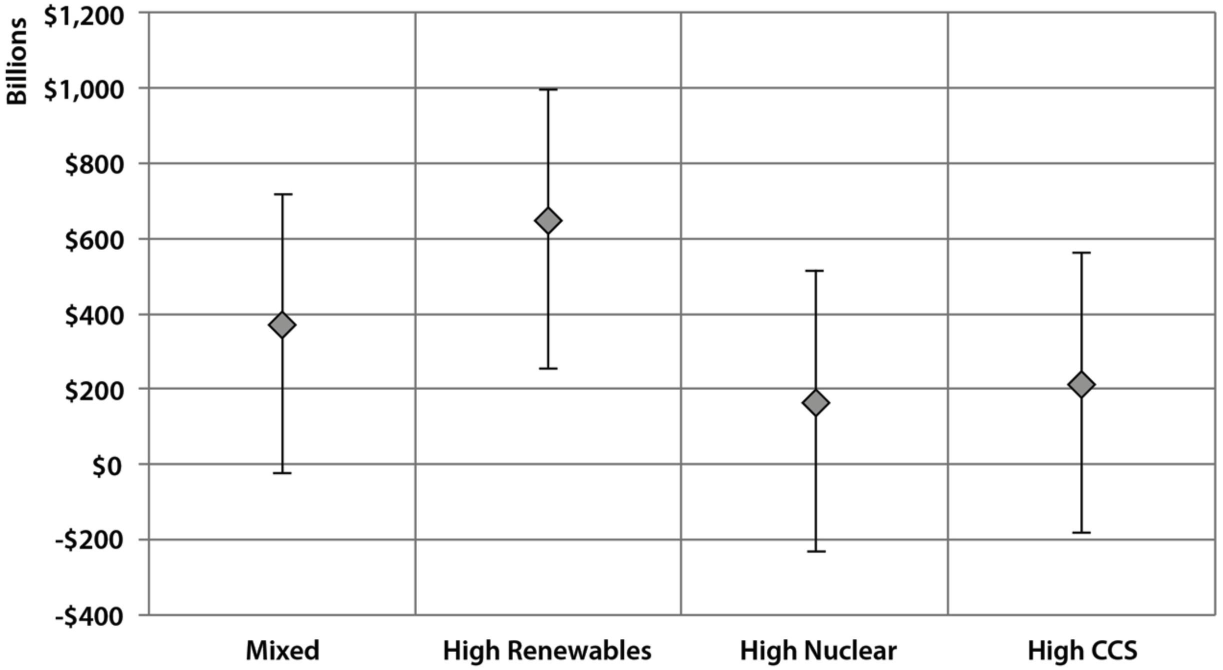
[18] A debate has emerged in this literature concerning the portfolio of clean energy technologies and energy carriers necessary for the transformation (see for example, Clack et al., 2017).

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

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

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

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



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

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

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

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

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

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

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

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

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

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

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

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

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

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

3.9 Synthesis, Knowledge Gaps, and Key Challenges

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

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

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

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

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

SUPPORTING EVIDENCE

KEY FINDING 1

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

Description of evidence base

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

Major uncertainties

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

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

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

Summary sentence or paragraph that integrates the above information

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

KEY FINDING 2

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

Description of evidence base

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

Major uncertainties

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

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

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

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

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

Summary sentence or paragraph that integrates the above information

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

KEY FINDING 3

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

Description of evidence base

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

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

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

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

Major uncertainties

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

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

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

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

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

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

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

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

Summary sentence or paragraph that integrates the above information

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

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

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

KEY FINDING 4

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

Description of evidence base

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

Major uncertainties

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

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

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

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

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

Summary sentence or paragraph that integrates the above information

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

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4 Understanding Urban Carbon Fluxes

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KEY FINDINGS

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

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

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

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

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

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

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

4.1 Introduction

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

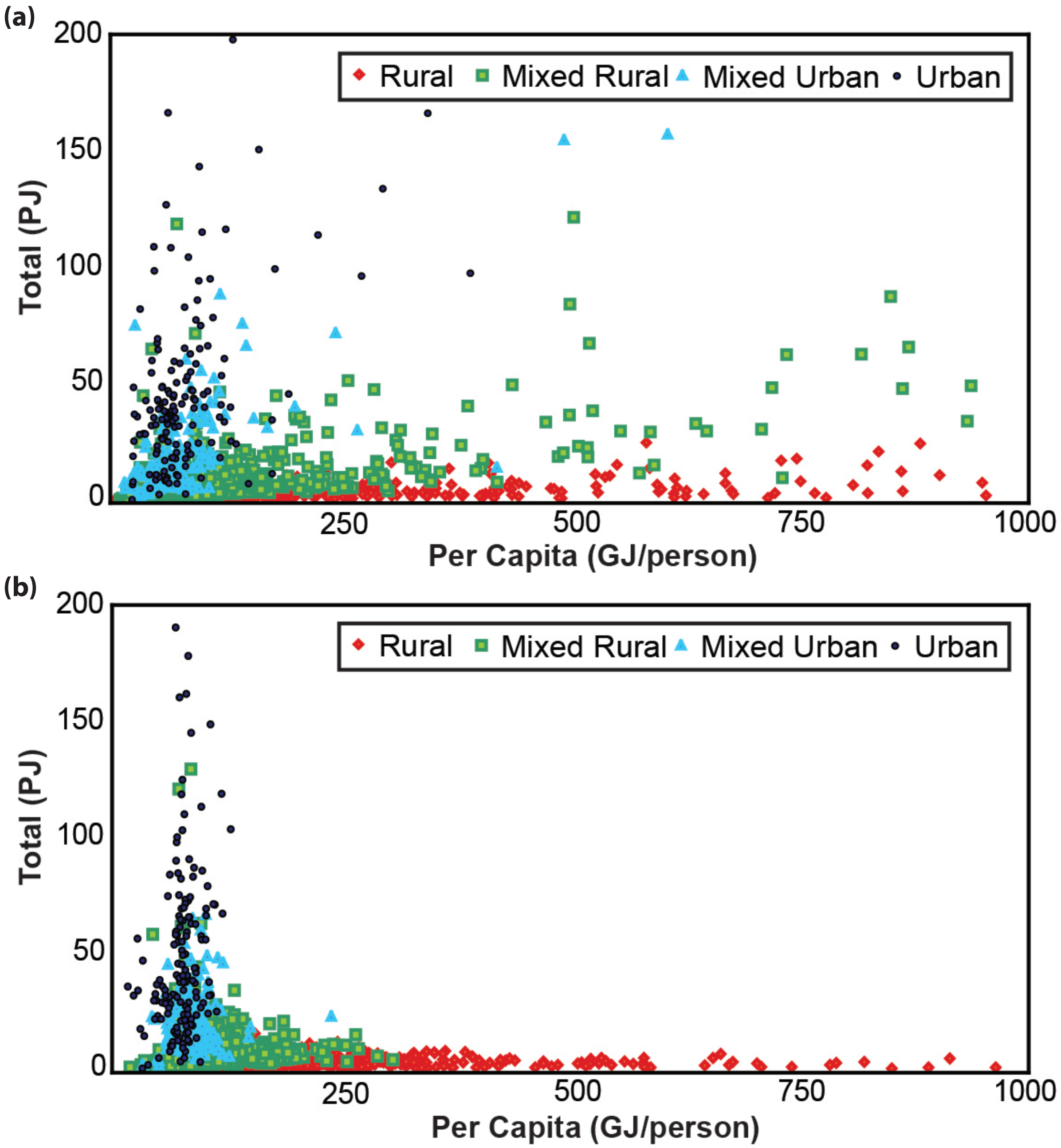

Figure 4.1. Per Capita Energy Consumption Versus Total Energy Consumption in Rural to Urban U.S. Counties. (a) Direct energy consumption measured in petajoules (PJ) and gigajoules (GJ) in building and industry and **(b)** direct energy consumption for transportation. [Figure source: Reprinted from Parshall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

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

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

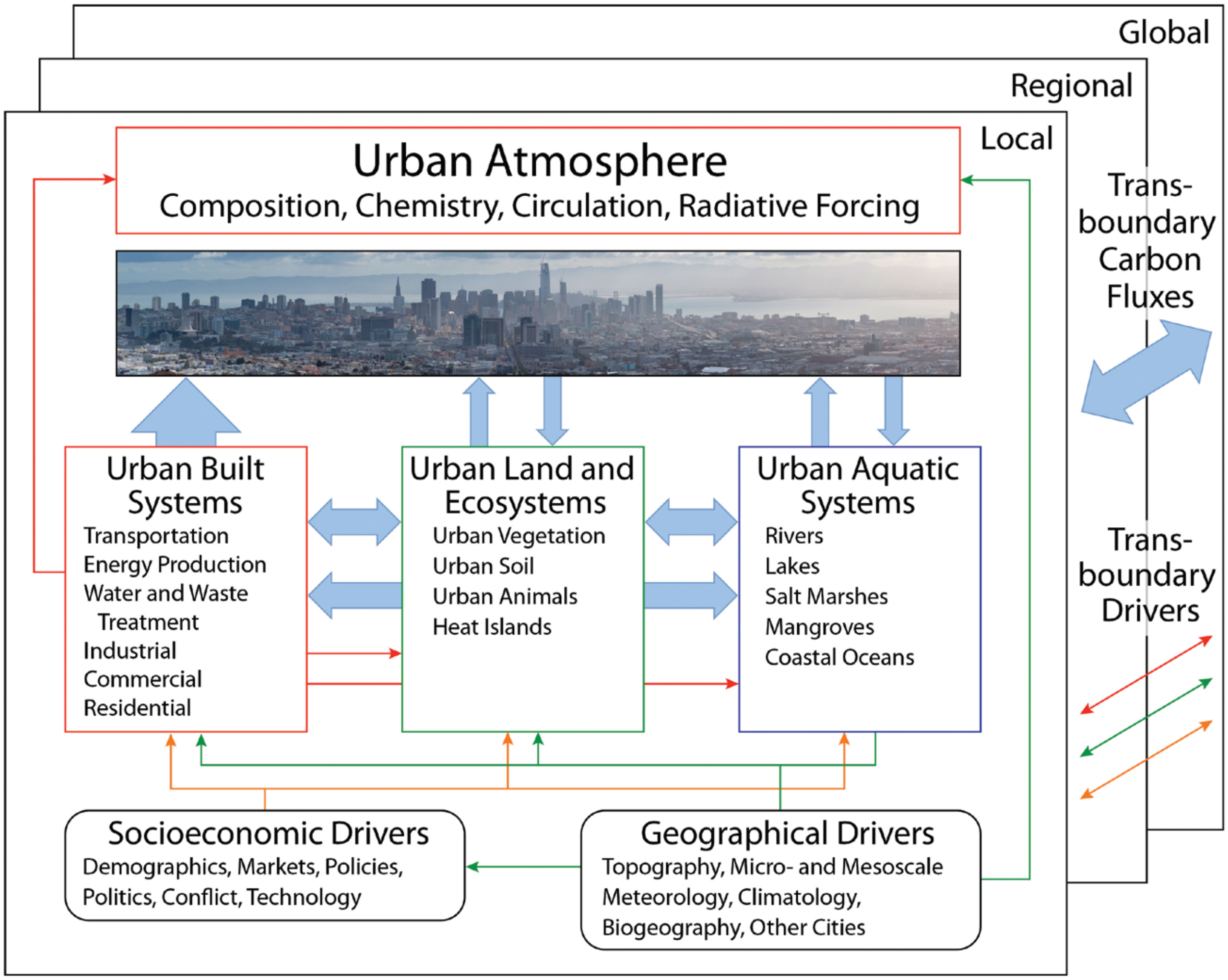

Figure 4.2. Key Components of Urban Carbon Cycling. Major reservoirs and processes (colored boxes) are depicted, along with carbon (C) emission and removal fluxes (blue block arrows), major drivers (oval boxes), and examples of process linkages (colored thin arrows). Outer boxes depict the relationships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

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

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

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

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

4.2 Current Understanding of Carbon Fluxes and Stocks

4.2.1 Accounting Framework and Methods

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

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

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

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

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

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

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

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

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

4.2.2 Human Activity and the Built Environment

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

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

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

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(Continued)

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

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

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(Continued)

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

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

Notes

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

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

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

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

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

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

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

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[1] Also see unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/9492.php.

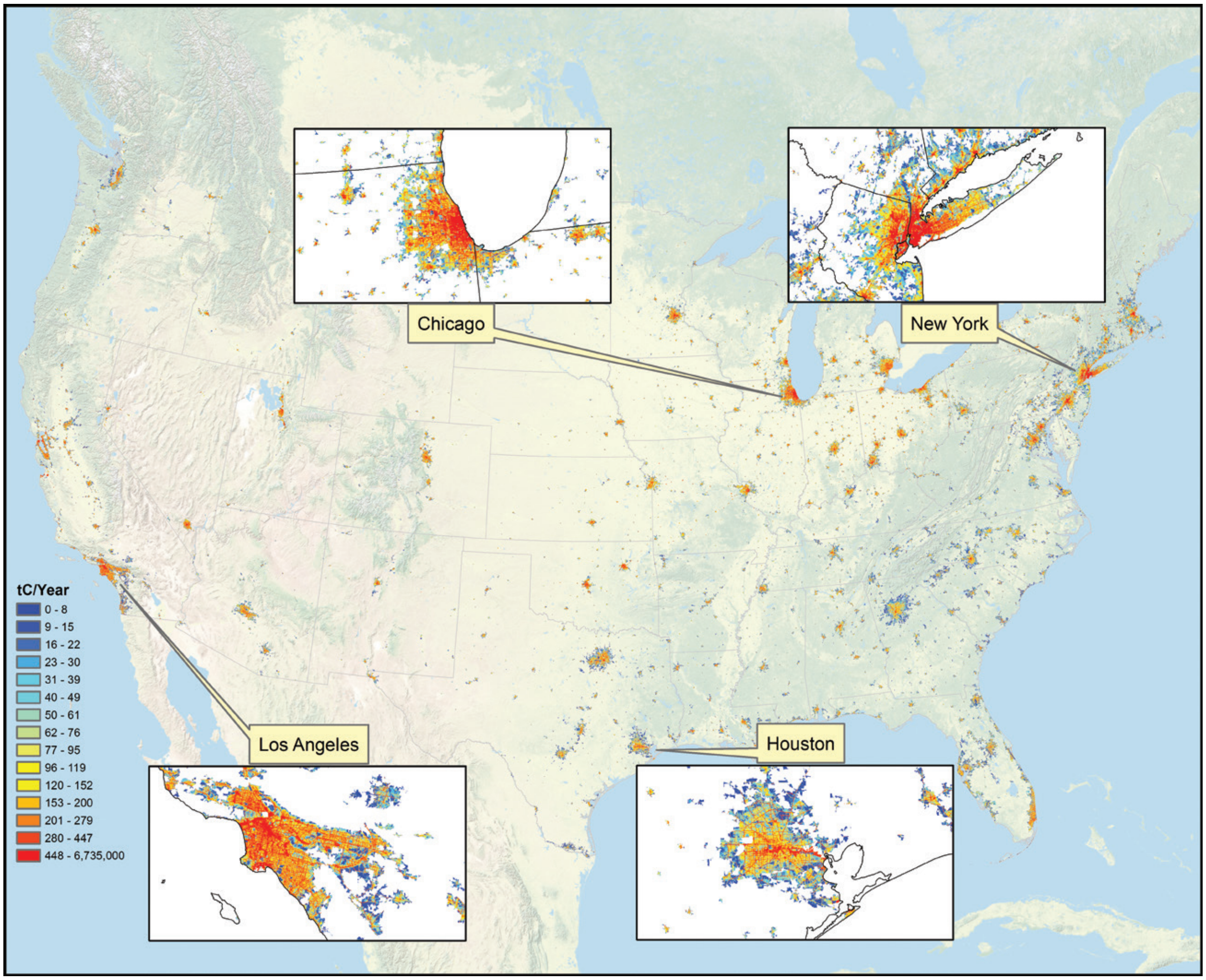

Figure 4.4. U.S. Fossil Fuel Carbon Emissions, Highlighting Four Urban Areas. [Data source: Gurney et al., 2009; units in log 10 tons of carbon (t C) per year.]

2012). (See Ch. 3: Energy Systems, p. 110, for details of leaked CH_4 emissions at the regional scale.) A study of CH_4 emissions from 13 urban distribution systems showed that emissions were roughly a factor of two smaller than U.S. Environmental Protection Agency (EPA) estimates, suggesting possible improvements in leak detection and maintenance work. However, the different methodologies between the two approaches would make assessing changes in leakage rates difficult (Lamb et al., 2015). At the same time, CH_4 emissions downstream from natural gas consumption meters on homes, buildings, and industrial facilities seem to be much higher than expected. A study in the San Francisco region suggests that emissions from the natural gas system can be equivalent to 0.3% to 0.5% of the region's natural gas consumption (Jeong et al., 2017). A similar study for the Los Angeles region estimates emissions at about 1.6% of consumption (Wunch et al., 2016). Los Angeles emissions may be higher because this region produces crude oil and natural gas. Aircraft mass balance and tower-based atmospheric inversions in Indianapolis differed by a factor of two and also exceeded the emissions estimated from a bottom-up inventory (Lamb et al., 2016).

This difference suggested that the aircraft estimate and the inventory did not account for widespread distribution of relatively small diffuse sources. These comparisons are complicated by the fact that they do not overlap in time and that emissions may be quite episodic and vary temporally. Long-term trend studies with sufficient precision to detect changes over time do not yet exist in the literature.

Methane also is produced by municipal waste facilities. In Toronto, these facilities account for as much as 10% of urban emissions (City of Toronto 2013); in Indianapolis, about 35% of emissions are attributed to one landfill (Cambaliza et al., 2015; Lamb et al., 2016).

4.2.3 Land and Ecosystems

Urban development directly and indirectly alters above- and belowground vegetation carbon pools and fluxes through land clearing, removal of vegetation, and disruption of soils (Raciti et al., 2012). Estimates of urban vegetation carbon densities vary substantially among cities or states and are based on extrapolation of limited, nonrandom sampling. Using extensive remote sensors and field observations, case studies in both Maryland and Massachusetts found that developed areas hold about 25% of the biomass per unit area of nearby forests (Huang et al., 2015; Raciti et al., 2014). Trees in urban areas in the United States and Canada store an estimated 643 teragrams of carbon (Tg C) and 34 Tg C, respectively (Nowak et al., 2013). In contrast, studies in xeric ecosystems show relative enhancement in urban biomass densities that result from landscaping preferences and addition of non-native vegetation (McHale et al., 2017).

Growing conditions for vegetation in urban areas typically differ from nonurban ecosystems, potentially accelerating the cycling of carbon and nutrients (Briber et al., 2015; Reinmann and Hutyra 2017; Zhao et al., 2016). For example, urban areas experience elevated ambient air temperatures (i.e., the "urban heat island" [UHI] effect; Oke 1982). These elevated temperatures cause seasonally dependent changes in carbon fluxes from urban vegetation and soils (Decina et al., 2016; Pataki et al., 2006; Zhang et al., 2004; Zhao et al., 2016), altering the length of the urban growing season (Melaas et al., 2016; Zhang et al., 2006). Urban respiration and growth patterns also may differ due to human additions of water and fertilizers, removal or addition of labile carbon sources (e.g., leaf litter and mulch), and planting preferences (Templer et al., 2015). Urban vegetation also can influence local climate and energy use (Abdollahi et al., 2000; Gill et al., 2007; Lal and Augustin 2012; Nowak and Greenfield 2010; Wilby and Perry 2006). For example, urban trees may affect building energy consumption and associated carbon emissions directly through shading of building surfaces and altered use of cooling equipment (Raji et al., 2015) and indirectly through local reductions in air temperature (Nowak 1993; Sailor 1998). These effects require accounting for water and energy penalties associated with irrigation of managed urban vegetation (Litvak et al., 2017). In addition, fertilization of urban landscapes and management practices such as lawn mowing can carry a high energy cost that must be assessed when determining the net effect of urban vegetation on the carbon cycle (McPherson et al., 2005; Townsend-Small and Czimczik 2010).

4.3 Societal Drivers

Investigations across a variety of research disciplines (e.g., urban economics, urban planning, urban geography, and urban physics) have tried to discern the driving factors of per capita urban carbon fluxes. International comparisons have demonstrated that economic factors such as available income and energy price levels play crucial roles, but so do urban density profiles, building age and construction, climate, and technology (Creutzig et al., 2015a).

4.3.1 Consumption

Manufacturing of goods such as clothing emits carbon if energy consumption is satisfied by fossil fuels, but consumption of goods and services, production systems, and supply chains are the fundamental drivers of emissions. As mentioned in Section 4.2.1, p. 193, accounting frameworks that

reflect a consumption perspective will allocate to the importing consumer the carbon fluxes associated with the production of goods and services. In particular, urban populations in wealthier nations that are nominally decarbonizing or stabilizing their carbon emissions often have total emissions that are increasing once traded carbon is considered in this way (Baiocchi and Minx 2010; Peters et al., 2011). Movement of goods among nations often is a result of trade policy, labor, and land costs that drive production location choices (Hertwich and Peters 2009). In U.K. cities, for example, a large carbon footprint is embedded in trade with large import partners such as China (Baiocchi and Minx 2010; Minx et al., 2013). Trade agreements, such as the North American Free Trade Agreement, have shifted automobile production and clothing manufacturing, along with their associated carbon emissions, from the United States to Canada and Mexico (Shui and Harriss 2005).

4.3.2 Economics—Wealth and Energy Prices

Economic development and urbanization reinforce each other through co-location of activities and investments (Fujita et al., 1999). In a global typology of cities, per capita gross domestic product (GDP) is identified as the most relevant sorting variable; transportation fuel prices also are relevant, distinguishing emissions among richer cities (Creutzig et al., 2015a). Urban development theories suggest that factors such as the clustering of investment and production, land development and transportation policies, and fuel prices shape urban form over the long run. For instance, incentives for dense urbanization exist when fuel prices are high and for sprawled suburbanization when prices are low, though legacy land uses—initiated during low fuel prices—continue to drive private automobile transportation use (Creutzig 2014; Fujita 1989). More recent urbanization patterns in mature cities have trended toward rehabitation or gentrification of urban cores. However, more time is needed to know the long-term impact of these patterns and whether they represent a shift toward lower GHG emissions due to less reliance on automobiles (Florida 2010). Cities also create new public transportation systems to reduce automobile dependence, but carbon fluxes from infrastructure creation remain significant in the short term (Chester et al., 2013). In an international comparison, the United States belongs to a grouping of countries with high incomes but low fuel prices. A nationwide study estimating U.S. household flux at the zip code level found that the number of vehicles per household and annual household income were the most relevant variables explaining estimated household carbon emissions (Jones and Kammen 2014). This finding illustrates the difficulties of meeting multiple policy objectives in most North American cities; when priority is given to development and urbanization, there are implications for the carbon cycle (Romero-Lankao et al., 2015, 2017).

4.3.3 Behavior—Lifestyles and Norms

Urban mobility in North America is dominated by personal automobile use, shaping and reconfiguring daily urban life (Sheller and Urry 2000). Lifestyles and norms clearly play a powerful role in explaining everyday decisions about urban mobility and energy use, but their importance as drivers for carbon emissions generally has not been studied quantitatively (Axsen and Kurani 2012; Mattauch et al., 2016; Wilson and Dowlatabadi 2007). In the United Kingdom, lifestyle changes could contribute as much to climate mitigation in the transport sector as technological changes (Anable et al., 2012). A typology of residential carbon emissions reveals that infrastructure patterns are mirrored in lifestyle classes. For example, low-emitting households in the dense urban cores of London and some U.S. cities typically are either "young professionals" or "multicultural inner city" communities of young people seeking inner-city living with downsizing or elimination of personal automobiles. Households in peri-urban London having higher emissions mostly identify as "affluent urban commuters" living in relatively inefficient houses (Baiocchi et al., 2015). However, whether these patterns are indicative of a long-term shift or merely a short-term adjustment is unclear. Another example from the Los Angeles Energy Atlas finds that wealthy neighborhoods have

higher per capita energy consumption than low-income residents who have higher consumption per unit area (Porse et al., 2016). In Salt Lake City, Utah, increments of wealth among high-income residents were found to lead to greater residential CO_2 emissions than those of low-income residents (Patarasuk et al., 2016). A systematic investigation of lifestyles, especially in interaction with urban infrastructures, has been identified as a major priority for further research (Creutzig et al., 2016). Social norms and behavior patterns in terms of energy use and consumption also exhibit carbon "lock-in," whereby norms act in isolation and in concert with institutional and technological constraints to add inertia to existing patterns of consumption and carbon emissions (see further details in Section 4.3.5, this page).

4.3.4 Urban Form and Density

Research has identified urban form and the density of cities as key drivers of urban carbon emissions (Baiocchi et al., 2015; Creutzig et al., 2015a; Karathodorou et al., 2010; Mindali et al., 2004; Newman and Kenworthy 1989, 1999). In theory, dense settlement affords energy efficiencies by encouraging multidwelling living, reduced travel distances, public transit use, and walking and cycling (Boyko and Cooper 2011; Oleson et al., 2008). In the United States, analysis has shown declines in per capita carbon emissions with increasing population density at densities greater than 1,158 persons per km^2 (Jones and Kammen 2014). At lower densities, typical of suburban areas, carbon emissions rise with increases in density (Glaeser and Kahn 2010; Jones and Kammen 2014). These results are supported by recent research on transportation energy consumption (Liddle 2014), electricity consumption in buildings (Lariviere and Lafrance 1999), and overall urban carbon emissions (Marcotullio et al., 2013). A recent study found that the high correlation between per capita electricity use and urbanized area per person can be explained by the higher per capita building floor area in less-dense cities (Kennedy et al., 2015).

Urban form and density are determined by local plans, existing infrastructure, land costs, and public attitudes (Ewing and Rong 2008). These factors often are determined by local actions and constrained by national, state, or other regulations, such as the Federal Emergency Management Agency's 100-Year Flood Maps, insurance policies, and perceived costs of existing infrastructure and land. Change in land-use patterns, as well as services such as public transportation, require long-term commitment, public support, and funding. Once a pattern has been set, it tends toward obduracy, making change difficult (Unruh 2000). Zoning codes that segregate land uses contribute to urban sprawl and a car-dependent road infrastructure that, in turn, influences carbon emissions (Fischel 2015; Hamin and Gurran 2009). These rules vary across states, provinces, and cities because of different relationships of autonomy between cities and other governmental scales. Policy drivers may be generated at the different scales, including national (e.g., transportation infrastructure investments), state, provincial (e.g., requirements for cities to create general plans or set building codes), or city (e.g., specific zoning codes; Knaap et al., 2015). These rules, codes, and standards establish frameworks for cities, including facilitating sprawled urban form through road subsidies or land regulation or encouraging density and efficient building through strict building codes and tax policy that discourages automobile use and ownership (Grazi and van den Bergh 2008). Stricter land-use regulation can induce sprawl development in nearby suburban and peri-urban areas, an occurrence that may increase overall carbon emissions. That is, cities with stricter land-use regulations externalize development to adjacent communities with more lenient regulations, engendering higher rates of suburbanization in the region (Glaeser and Kahn 2010). Harmonization of land-use regulation or higher fuel taxes can reduce the likelihood of this outcome.

4.3.5 Technology

Technological attributes, such as power generation (see Ch. 3: Energy Systems, p. 110), urban design, and waste processing, partly determine city profiles for carbon emissions (Kennedy et al., 2009). Availability of low-carbon technologies reduces urban per

capita carbon emissions. For example, cities with carbon intensity of electricity below approximately 600 metric tons (t) CO_2 equivalent[2] (CO_2e) per gigawatt hour (GWh), such as Los Angeles, New York City, and Toronto, can reduce life cycle carbon emissions through electrification of transportation and heating systems (Kennedy 2015; Kennedy et al., 2014). However, because of the relative permanence of large technological and infrastructural systems in urban areas, the notion of infrastructure lock-in is critical and often makes shifts to low-carbon technologies and systems costly or not feasible (Unruh 2000). Lock-in results from the high cost of the infrastructure; the expended energy in the infrastructure; and the social systems of regulation, codes, and conventions that reinforce existing systems (Pincetl et al., 2016; Reyna and Chester 2015; Seto et al., 2016). However, technology is influenced by institutions, individual behavior, and policy actions (Chester et al., 2014), and technology has replacement or turnover cost implications with fossil fuel–burning infrastructure having lifetimes of up to 50 years (Erickson et al., 2015; see Figure 4.5, p. 204). The issue of carbon lock-in is another example of the interactions, constraints, and opportunities that involve multiple scales of governance beyond urban domains.

In 16 U.S. states and Washington, D.C., regulatory changes, such as Incentives for Renewables and Efficiency, are both facilitating and requiring decarbonization of energy (www.nrel.gov/tech_deployment/state_local_governments/basics_portfolio_standards.html). U.S. public utilities commissions (PUCs) regulate the large investor-owned utilities, and PUCs of states such as New York and California are creating new regulatory frameworks for increased renewable energy generation, purchase, and storage to decrease reliance on fossil fuel–generated energy. In 2015, California established a 50% renewable portfolio standard for the electricity system that is to be accomplished by 2030 (Senate Bill 350). The state also adopted a new legal mandate in September 2016 requiring statewide reductions of GHG emissions by 40% from 1990 levels by 2030 (Senate Bill 32).

4.3.6 Climate

Local climate is also a modifier of urban carbon emissions in conjunction with socioeconomic and urbanization characteristics (Baiocchi et al., 2015; Creutzig et al., 2015a; Glaeser and Kahn 2010; Kennedy et al., 2015). Global climate change typically modifies local energy use by reducing heating and increasing air conditioning demands (Huang and Gurney 2016). Local climate also can be partly influenced by human activity via the UHI effect (Boehme et al., 2015; Georgescu et al., 2014; Oke 1982), which, in turn, drives changes in energy consumption and carbon emissions (Lin et al., 2015; Wang et al., 2010).

4.4 Trends and Feedbacks

A quantitative understanding of contemporary urban carbon trends continues to face limitations related to data availability across the North American domain. Some understanding can be gleaned from statistics on urban growth in general, along with several case studies of urban carbon fluxes over particular time spans or locations. For example, Mexico's annual urban population grew at a rate of 1.9% between 1995 and 2015, while both Canada and the United States had urban growth rates of 1.2% (UN DESA 2015). Future projections at the global level and for North America suggest increases in urban land use. For example, there is a greater than 75% probability that global urban land will increase from 652,825 km^2 in 2000 to 1,863,300 km^2 in 2030 (Seto et al., 2012). Other studies have projected a near tripling in the percentage of land devoted to urban cover by midcentury (Nowak and Walton 2005).

The future trajectory of urban carbon fluxes is unambiguously tied to increases in aggregate urban energy demand and the proportion met by fossil fuels (Hoornweg et al., 2011; Jones and Kammen 2014; Marcotullio et al., 2013). Theoretically, these

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

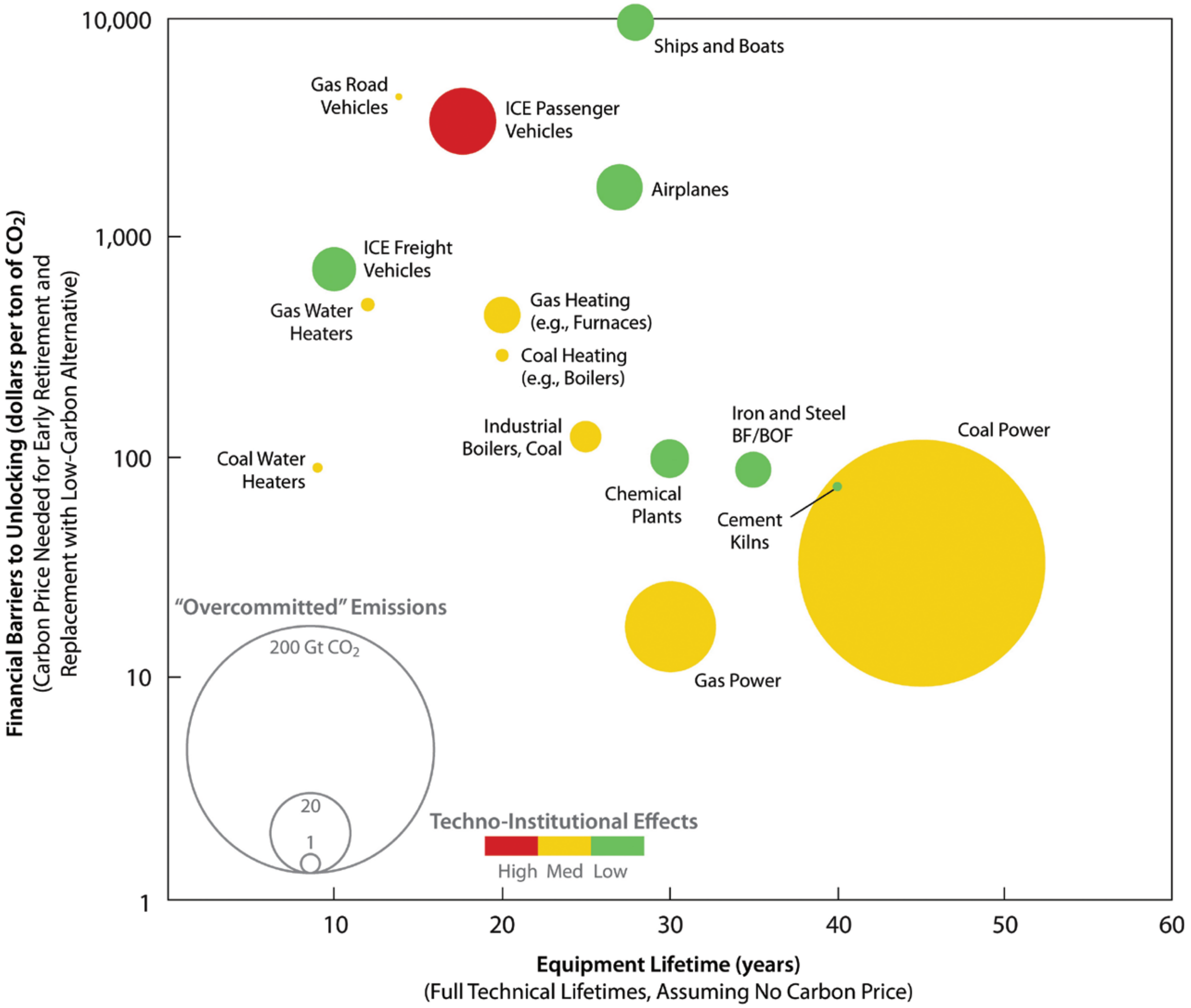

Figure 4.5. Assessments of Lock-In Related to Different Types of Infrastructure Emitting Carbon Dioxide (CO_2). Different fossil fuel–burning infrastructures are plotted according to their historical lifetime (x-axis) and the carbon price (in dollars per ton of CO_2) required to equalize the marginal cost of existing infrastructure (mainly fuel) with the total levelized cost (i.e., including capital and operating expenses) of a low-carbon replacement (y-axis). Circle sizes reflect the cumulative future emissions of each type of infrastructure that are in excess of what that infrastructure can emit under a 2°C climate scenario. Colors are qualitative indicators of the techno-institutional resistance of that type of infrastructure to unlocking (e.g., stocks of very specific intellectual capital, established subsidies, entrenched social norms, large supporting infrastructures, and political influence). Key: ICE, internal combustion engine; BF, blast furnace; BOF, basic oxygen furnace; Gt, gigaton. [Figure source: Redrawn from Seto et al., 2016 (originally adapted from Erickson et al., 2015), used with permission.]

increases are the cumulative result of concentrated population and economic activity, which today are predicated on the more energy intensive processes in agriculture, transportation, buildings, industry, and waste management (Liddle 2014). However, despite consensus about the positive correlation between population and energy demand or carbon emissions, there is debate about the magnitude of the effect and the implications of future urbanization. The effect of population size on carbon

emissions or energy demand may be contingent on other factors, including, for example, a city's starting population size (Bettencourt et al., 2007). Some evidence for this scaling relationship suggests that urban areas with larger population sizes have proportionally smaller energy infrastructures than smaller cities (Bettencourt et al., 2007; Fragkias et al., 2013). Other evidence suggests that carbon emissions may increase at a rate greater than population growth rates, so that larger cities exhibit proportionally higher energy demand as they grow than do smaller cities (Marcotullio et al., 2013). Theoretically, such an outcome is possibly due to diminishing returns, threshold effects, negative synergisms, and the disproportionate escalation of cost for maintaining environmental quality with population growth (Ehrlich and Holdren 1971). Finally, the difficulty occurs with predicting not only trends in policymaking, but also the impact of policy change on energy sources (Tuckett et al., 2015). For instance, in some U.S. states, policy is shifting some of the energy generation toward renewables (Lutsey and Sperling 2008). However, cost drivers for energy sources evolve over time and influence the choice of energy supply (Gan et al., 2007).

The generation of waste heat, coincident with carbon emissions from the combustion of fossil fuels, has the potential to initiate feedbacks with the urban carbon cycle through the UHI effect—a phenomenon whereby urban areas are warmer than their unbuilt surroundings (Boehme et al., 2015; Oke 1982). Averaged at the city scale, the magnitude of this waste heat can be up to 100 watts per m^2 (Sailor et al., 2015), potentially increasing urban warming by 2 to 3°C in winter and 0.5 to 2°C in summer (Fan and Sailor 2005). As urban areas warm due to both large-scale changes in climate and localized UHI, the energy consumed for space cooling in summer increases while the energy used for heating in winter decreases, "spilling over" into other seasons (Li et al., 2015; Wang et al., 2010). For example, recent research found that summer electricity demand may increase up to 50% in some U.S. states at the end of this century due to increased cooling needs under climate change alone (Huang and Gurney 2016). In fact, a recent modeling study by Georgescu et al. (2014) found that for U.S. cities, the effects of urban expansion on urban air temperatures by 2100 will be on the same order of magnitude as GHG-induced climate change. The UHI effect, in addition to changes in heatwave event frequency and magnitude, would further exacerbate this feedback (Li and Bou-Zeid 2013).

4.5 Global, North American, and Regional Context

4.5.1 Global Urban Carbon

Of the nearly 1,000 urban agglomerations with more than 500,000 people across the world, three-quarters are in developing countries (UN DESA 2015). The share of energy-related urban CO_2 emissions worldwide is 71%, somewhat less than the share in North America (IEA 2008). Given the greater levels of current urbanization in North America and recent trends across the world, most future urban growth and associated urban carbon emissions likely will be dominated by low- and middle-income countries. In smaller urban areas within the United States and Europe, de-urbanization is occurring (Martinez-Fernandez et al., 2012), and its implications for carbon emissions are still poorly understood.

Within the global context, North America (particularly Canada and the United States) has smaller urban population densities but greater per capita built-up area (Seto et al., 2014). Due to extensive urbanization levels and fossil fuel consumption associated with transportation and urban infrastructure, North America has the largest percent of total carbon emissions emanating from urban areas (Marcotullio et al., 2013).

4.5.2 United States, Canada, and Mexico—Urban Carbon in Context

Cities in the United States and Canada generally have recorded amongst the highest per capita carbon emissions when compared to global cities (Dodman 2009; Hoornweg et al., 2011; Kennedy et al., 2009; Sovacool and Brown 2010). In cities for which there

are repeat carbon inventories (e.g., Boston, New York City, Toronto, and Seattle, from 2004 to 2009), per capita emissions are declining at the same rate as national inventories (Kennedy et al., 2012). But when indirect emissions are included in city inventories, urban per capita emissions are about the same as national per capita emissions (Ramaswami et al., 2008). This measurement further highlights the importance of understanding indirect carbon fluxes and the increase in the export of emissions outside the North American urban domain. Core aspects of per capita energy and material consumption have been found to be inversely correlated to urban population density (Kennedy et al., 2015).

4.6 Carbon Management Decisions

Since the mid-1990s, cities around the world have increasingly engaged in carbon management efforts, reflecting a growing recognition that cities are both locations where emissions-producing activities occur and political jurisdictions with authority over some of those activities (Castan Broto and Bulkeley 2013). The number of cities that have committed to some form of carbon reduction has increased exponentially, from fewer than 50 in the early 1990s, several hundred by the early 2000s (Bulkeley and Betsill 2003), and several thousand a decade later (Krause 2011; Pitt 2010). North American cities have played a particularly important leadership role, emerging as key sites for experimentation and innovation with different types of policies, technologies, and programs (Burch 2010; Castan Broto and Bulkeley 2013; Hoffmann 2011; Hughes and Romero-Lankao 2014, 2015).

4.6.1 Importance of Governance and Multilevel Networks

Key factors in the ability of city governments to manage carbon emissions are the mandates and competencies of municipal governments, financial resources, presence of political champions, multilevel networks, an open political opportunity structure, and the ability to capitalize on co-benefits valued by local residents (Betsill and Bulkeley 2007; Ryan 2015). Local authorities in North America also encounter a number of barriers, including the lack of coordination across different parts of city government, sunk investments in infrastructure, and resistance to change of the local political economy (Romero-Lankao et al., 2013, 2015; Sharp et al., 2010; Tang et al., 2010; Tozer 2013). A recent study found that U.S. city membership in the International Council for Local Environmental Initiatives (ICLEI) declined 22% between 2010 and 2012 and that large numbers of cities had abandoned their climate policy efforts altogether (Krause 2015).

Local carbon mitigation efforts also are limited by infrastructure lock-in and "path dependencies" created from previous policy decisions and investments, which can make changing direction politically difficult and expensive (Unruh 2000). Path dependency is a function of infrastructure cost and life cycle and is influenced by the way that decisions are made (Romero-Lankao et al., 2017). For instance, the low-density urban form of North American cities such as Los Angeles has been largely the result of freeway construction programs of the California Division of Highways (Wachs 1993). These decisions have created a path-dependent use of private vehicles, associated with more energy use and more carbon emissions (Kenworthy 2006).

There is one important difference in the policy contexts of cities in the United States, Canada, and Mexico. Cities occupy different jurisdictional space and face different economic, institutional, and political contexts. Decision making in the United States is generally more decentralized than that in Canada and Mexico, potentially giving city governments more autonomy (Bulkeley and Betsill 2013). Notwithstanding these across-country differences, the challenges and opportunities cities face, such as economic development, air pollution, and transit access, vary as much within countries as between them. For example, policy aimed at mitigation of local air pollution has resulted in climate policy co-benefits in most large North American cities, including Mexico City, but results typically are not as salient for smaller cities (Romero-Lankao 2007).

While municipal governments have some control over carbon emissions, urban carbon management ultimately takes place in a multilevel governance context, whereby climate policy efforts have the potential to be spread across different levels of political jurisdiction and pursued through diverse forms of governance instruments (see Ch. 3: Energy Systems, p. 110; Ch. 6: Social Science Perspectives on Carbon, p. 264; and Ch. 18: Carbon Cycle Science in Support of Decision Making, p. 728). For example, utilities can be governed by federal, regional, and state institutions and by public, private, and nonprofit partnerships that each make decisions on policy, infrastructure, and the mix of power generation in the electricity grid (Bulkeley 2010; Pincetl et al., 2016; Schreurs 2008). Municipal priorities and outcomes are shaped not only locally, but also by international agreements; national policies, legislation, and regulation; and state- and provincial-level efforts such as the adoption of renewable portfolio standards and the initiation of emissions trading markets (Bulkeley 2010; Bulkeley and Betsill 2013; Burch 2010; Romero-Lankao et al., 2017). National and state or provincial policies shape urban management efforts by creating a permissive or restrictive institutional setting for local action (Bulkeley and Betsill 2013; Burch 2010; Homsy and Warner 2014; Romero-Lankao et al., 2013, 2015, 2017). For example, federal and state agencies (e.g., public utility commissions) independently shape a number of energy-supply characteristics through rules, regulations, and standards. In California, state-level regulations are playing a significant role in spurring local action, such as calling for Zero Net Energy residential buildings by 2020, doubling energy efficiency for the existing building stock by 2030, and meeting renewable portfolio standards. In many North American cities, there is relatively little explicit interaction or coordination among these different levels of government (Betsill and Rabe 2009; Jacoby et al., 2014).

Thousands of North American cities and towns have joined municipal networks such as the C40 Cities Climate Leadership Group and the ICLEI (Kern and Bulkeley 2009; Robinson and Gore 2011), though participation is declining, as noted. Municipal climate change networks play a role in generating norms and standards for setting targets and monitoring and measuring progress (Betsill and Bulkeley 2004). These networks also provide opportunities for information sharing and capacity building. Cities join such networks to demonstrate leadership and secure recognition. However, the impact of network membership on local implementation or broader-scale policy change has yet to be demonstrated (Gore 2010; Krause 2012).

4.6.2 Sectoral Mitigation Approaches

Three urban sectors have been identified as key for mitigating urban carbon emissions: the built environment, transportation, and energy systems (see Section 4.2.2, p. 195). Carbon emissions from energy use in buildings can contribute as much as 80% of a city's total and primarily are controlled by private building owners (Rosenzweig et al., 2010). As a result, states and local authorities in many North American cities have begun to partner with private actors—the owners of these buildings—to integrate carbon mitigation and transition to low-carbon development within broader urban agendas (Bulkeley and Betsill 2013; Bulkeley and Castán Broto 2013; Hodson and Marvin 2010; While et al., 2010). Reducing energy consumption through energy-efficient building design and construction is an ongoing effort at the state and local levels in North America (Griego et al., 2012; Koski 2010; Larsson 1999). Mexico hosts the seventh largest green building market in the world,[3] and Canada is the largest green building market outside the United States. Cities also can incentivize or require energy conservation more directly. Energy-use benchmarking policies for the private sector are being promoted for North American cities, several of which have adopted these policies including New York City, Philadelphia, San Francisco, and Seattle (Cox et al., 2013). New York City's Greener, Greater Buildings program benchmarks energy use in private buildings and mandates energy efficiency

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[3] www.gbes.com/blog/mexico-is-a-leed-leader/

and conservation measures (Block and Semel 2010). Similarly, California's Senate Bill 802 may make benchmarking mandatory for commercial buildings.[4] These examples have informed the National Resources Defense Council's City Energy Project, which is helping cities introduce benchmarking and conservation efforts of their own. The actual performance of buildings also depends on correct equipment installation, occupant behavior, and attitudes toward energy conservation (Mills and Schleich 2012; Virote and Neves-Silva 2012). Additionally, local authorities in Toronto are piloting a carbon credit trading program, and many cities have placed energy use and efficiency at the center of their climate change mitigation efforts (IEA 2015; Sun et al., 2015). California's Title 24 building codes, first established in 1978, have required increasingly stringent energy conservation for buildings, including insulation, window glazing, and more. These codes are credited for much of the state's energy savings (CEC 2015), but there also is evidence for a rebound effect as buildings, though more efficient, are bigger overall (Porse et al., 2016). Finally, the energy embodied in building construction can be incorporated into green building policy (Biswas 2014; Hammond and Jones 2008; Reyna and Chester 2015). Accounting and labeling systems, for example, measure and inform consumers about the environmental impacts of a structure (Dixit et al., 2010; Monahan and Powell 2011).

Transportation mitigation options include facilitating the transition to lower-emission vehicles and expanding the availability and use of public transit (Creutzig et al., 2015b). Cities are building electric vehicle charging stations, requiring low-emission vehicles in their own fleets, and encouraging biking and walking. Transit-oriented developments are designed to reduce the carbon emissions correlated with low-density suburban sprawl (Glaeser and Kahn 2010), though high capital costs and fragmented decision making continue to pose challenges. Additional challenges include long-term tradeoffs regarding the carbon impacts of different transit and fuel-mix options that continue to be evaluated (Chester et al., 2013).

Because cities consume about 75% of power generation worldwide (Dodman 2009), a common mitigation focus for cities is energy production itself. Many cities do not have formal authority to dictate the fuel sources for their energy supply and thus must rely on action from other levels of government and the private sector (Kern and Alber 2009). Reliance and cooperation require indirect action on the part of city governments, such as facilitating or incentivizing the expansion of renewable energy sources and lobbying relevant decision-making bodies. Examples include Toronto and Halifax's use of deep lake water to cool buildings, though there are barriers to scaling up such technologies (Newman and Herbert 2009). At the same time, there is increasing understanding of the need to couple solar generation with storage. Currently, "excess solar" generated in the middle of the day is not stored, requiring other electricity generation sources for peak load times and in the evening. Often this energy is provided by natural gas "peaker" power plants that constantly are powered, emitting CO_2 (St. John 2014).

Cities often have more direct control in areas such as waste-to-energy schemes and local distributed solar generation. For example, CH_4 capture at two of Toronto's largest landfills is responsible for just over 10 million tons of GHG reductions since 2004 (City of Toronto 2007, 2015). In California, local governments have begun to create Community Choice Aggregation alternative utilities that offer customers greater proportions of renewable energy (Roberts 2015). Key to ensuring the success of these programs is maintaining the subsidies and incentives to overcome behavioral and technological challenges (Kammen and Sunter 2016).

Two additional urban carbon cycle components deserve mention when considering sectoral mitigation approaches: CH_4 leakage (referred to as "fugitive" emissions) and urban vegetation. As mentioned in Section 4.2.2, p. 195, several studies have identified CH_4 emissions from leaking

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[4] www.energy.ca.gov/sb350/

natural gas infrastructure serving cities (Jackson et al., 2014; Lamb et al., 2016; McKain et al., 2015; Phillips et al., 2013). Methane emissions also can occur downstream of building meters, for example, from leaky gas pipes in buildings, stoves, hot water heaters, and other appliances (Jeong et al., 2017; Lavoie et al., 2017; Wunch et al., 2016). The quantity of CH_4 emissions from the natural gas system is not well constrained (Brandt et al., 2014; Hendrick et al., 2016; Lamb et al., 2016; McKain et al., 2015), but there are specific thresholds for CH_4 loss from natural gas, which, if exceeded, would negate the climate benefit of switching to natural gas. According to Alvarez et al. (2012),[5] realizing an immediate net climate benefit from the use of natural gas would require CH_4 emissions from the natural gas system to be lower than 0.8%, 1.4%, and 2.7% of production to justify a transition from heavy-duty diesel vehicles, gasoline cars, and coal-burning power plants, respectively.

At the municipal scale, reports indicate that biological carbon uptake within urban boundaries constitutes 0.2% to 3% of total emissions, depending on the locality (Escobedo et al., 2010; Liu and Li 2012; Tang et al., 2016; Velasco et al., 2016). However, biological carbon respiration rates are sensitive to management practices (e.g., Decina et al., 2016), and urban vegetation possibly can constitute a net source of carbon to the atmosphere. The role of urban vegetation dynamics may be much more significant in affecting emissions through indirect impacts on the urban carbon cycle, such as shading of buildings that reduces energy consumption, evaporative cooling of urban vegetation, and wind sheltering (Akbari et al., 2001; Shashua-Bar et al., 2009; Susca et al., 2011). These indirect carbon reductions—a result of urban vegetation on energy consumption rather than direct carbon emissions–reducing technologies, for example—must be weighed against the energy and water penalty of increasing vegetation cover in locales with little or no historic vegetation canopy, such as the southwestern United States (Middel et al., 2014, 2015).

4.6.3 Co-Benefits and Tradeoffs—Links to Air Quality, Health, and UHI

Studies have identified co-benefits between carbon mitigation in urban areas and improvements in human health and other urban environmental issues (Harlan and Ruddell 2011; Milner et al., 2012; Viguié and Hallegatte 2012; see Ch. 6: Social Science Perspectives on Carbon, p. 264). For example, reducing fossil fuel consumption or CH_4 emissions also decreases emissions of traditional air pollutants such as carbon monoxide (CO), sulfur oxides (SO_x), volatile organic compounds (VOC), particulates, and oxides of nitrogen (NO_x). Three of these—NO_x, VOCs, and CO—are associated with the production of ground-level ozone, which is linked to respiratory diseases such as emphysema, bronchitis, and asthma (Kim et al., 2011). Various studies have linked fine particulate exposure to significant health problems including aggravated asthma, chronic respiratory disease in children, and premature death in people with heart or lung disease (Valavanidis et al., 2013). However, carbon mitigation practices also have tradeoffs. For instance, renewable energy systems that lower carbon emissions and reduce health impacts of traditional air pollutants are not completely free from environmental and health impacts (Miller et al., 2013).

Carbon emissions often are associated with waste heat production, which plays a role in the UHI effect. Strategies that reduce fossil fuel carbon emissions may contribute to reduced waste heat and, subsequently, a decrease in both summer and winter urban air temperatures. The magnitude of urban cooling may be modest and dependent on the location and timing of reduced energy consumption (Huang et al., 2013; Ostro et al., 2011; Sarofim et al., 2016) and the fuel mix used for electricity production and building heating systems (Jacobson and Ten Hoeve 2012).

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[5] These numbers were modified from the Alvarez et al. (2012) study by the Environmental Defense Fund to account for new data (see www.energy.ca.gov/2014_energypolicy/documents/2014-06-23_workshop/presentations/13_O_Connor_EDF_IEPR-Presentation.pdf).

4.7 Synthesis, Knowledge Gaps, and Outlook

Dozens of completed or underway studies on urban carbon flux are now reported in the peer-reviewed literature (see Table 4.1, p. 196). Among these are intensive efforts testing different methods and approaches to understanding flux magnitudes, trends, driving activity, emissions mitigation guidance, and reduction performance tracking. Despite these efforts, consistent and comparable data on carbon fluxes in cities are still lacking, particularly at spatial resolutions below the whole-city level (Kennedy et al., 2015). Greater integration of these studies and greater exploration of whether and how this information can be used by stakeholders are needed. This will require continued efforts in interdisciplinary integration of existing subcommunities engaged in urban carbon research. For example, the use of sometimes singular reliance on atmospheric concentration observations common in inversion studies could move toward an assimilation framework in which all available observational constraints are incorporated with their accompanying uncertainties to arrive at optimized carbon fluxes, further integrating bottom-up and top-down approaches. Equally important are 1) the integration of information on CO_2, CH_4, and relevant local air pollution and 2) the continued trend toward data with higher space and time resolutions, particularly relevant to urban stakeholders. Finally, integration across ongoing urban studies will provide more insight into which research methods and approaches are successful under differing urban morphologies and social and physical constraints (e.g., urban density, data transparency, and topography). These advances could be achieved in part by integrating existing approaches with remote sensing of urban CO_2 and other attributes relevant to the urban carbon cycle.

Urban carbon trends remain difficult to assess because of a lack of compatible and comparable data and limited historical information. Results from a number of intensive studies underway should begin to inform trend information in North America. Improvement to trend detection is critical to the assessment and prognostic capabilities important to urban stakeholders. Integration of urban trend detection with trend activity at larger scales could advance the ability of observing systems to systematically assess urban trends.

Urban carbon fluxes are dominated, directly and indirectly, by the human activities within the built environment that includes large infrastructural systems such as buildings, roads, and factories, along with their co-evolution with fossil fuel energy sources. The carbon fluxes associated with this co-evolved technological system are modulated by underlying climate and socioeconomic dynamics such as consumption, wealth, lifestyles, social norms, governance, and energy prices. A quantitative understanding of these drivers and flux outcomes remains difficult to generalize. This challenge is due to both the emergent properties of urban carbon fluxes and the idiosyncratic nature of cities and the studies performed thus far, which tend to focus on single urban domains. Particularly in Mexico, for example, little work has been accomplished outside the Mexico City metropolitan area. More research is needed that systematically explores multiple urban domains to better understand the relationships between emissions and the physical, social, and technological dynamics in cities.

The urban domain is a source of significant carbon mitigation potential evidenced by the rapid rise in individual urban-scale climate policy efforts. This mitigation, combined with the dominant role that cities play in total anthropogenic carbon emissions, implies that proposed emissions mitigation measures must be tested against documented success in urban areas. The ability of cities to manage carbon fluxes is determined by what control cities can exert over flux sources or their drivers. Cities and their carbon management efforts exist within a larger multilevel governance matrix that can both enable and hinder carbon mitigation efforts. For example, without control over energy supply systems, some cities have limited capability to mitigate emissions.

More targeted research evaluating how specific reductions in emissions are linked to specific policies would enhance the ability to design and implement effective policies in the future. There is limited evidence on the effects of urban climate policy on reducing community-wide emissions, advancing other urban policy goals, or contributing to a transition to low-carbon development. Attributing changes in urban carbon emissions to the actions of city governments also can be challenging, partly because of the complex networks of authority at play. Moreover, there has been little effort to study other effects of urban climate policy, such as cost-effectiveness, co-alignment with other goals and processes, and distributional effects on marginalized populations. Without common frameworks and comparable case studies, the extent to which local or distant political and economic factors shape these outcomes is unclear.

Given the increasing role that urban areas play in the total carbon fluxes within the three North American countries, there is a critical need to improve urban carbon flux projection capabilities in North American cities. Better information on fluxes and their drivers, combined with improved understanding of successful mitigation, would offer researchers and urban decision makers the means to bend urban flux trajectories toward low-carbon pathways. Continued work on the co-benefits and tradeoffs associated with carbon mitigation practices will further enrich carbon emissions planning to account for the important related issues of the UHI, urban air quality, and human health.

SUPPORTING EVIDENCE

KEY FINDING 1

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

Description of evidence base

Key Finding 1 is supported by empirical evidence and modeling studies aimed at quantifying and understanding urban extent, energy, carbon, and material flows (Jones and Kammen 2014; Hoornweg et al. 2011; Seto et al., 2014). Research has highlighted the importance of direct versus indirect carbon fluxes in addition to the relative importance of urban carbon flows within the national landscape (Lin et al., 2015).

Major uncertainties

Very few studies have attempted a comprehensive assessment of the urban portion of North American carbon emissions. Only two have attempted estimates for the North American domain (Marcotullio et al., 2013; Grubler et al., 2012). Both contain unquantified uncertainties acknowledged to include not only the underlying data, but also the definition of "urban" and objective methods to spatially enclose urban areas (Parshall et al., 2010). Uncertainty also exists in the exact quantification of urban versus nonurban carbon emissions because of limited data and methodological inconsistencies in defining direct and indirect carbon fluxes.

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

Key Finding 1 is supported by a growing number of urban carbon footprint studies in North America. Much of this work is in the United States, with some work in Canada and very few studies in Mexico. There is general agreement that urban areas constitute the majority of anthropogenic carbon emissions in North America. However, a more precise assessment remains uncertain because of a lack of comprehensive data. Recent formalization of methods now defines direct versus indirect anthropogenic carbon emissions, but these methods are applied inconsistently in studies of urban carbon emissions, challenging attempts to compare emissions among cities.

Summary sentence or paragraph that integrates the above information

For Key Finding 1, anthropogenic carbon fluxes associated with North American cities represent the majority of total anthropogenic carbon emissions from North America, though uncertainty remains on the precise share. These emissions consist of both direct and indirect emissions, the latter of which are recognized as important, but often poorly characterized, components of total urban anthropogenic carbon flux.

KEY FINDING 2

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

Description of evidence base

Key Finding 2 involves societal factors that drive urban carbon emissions, including consumption and supply chains (Baiocchi and Minx 2010; Peters et al., 2011), wealth (Creutzig et al., 2015a), fuel prices (Creutzig 2014), lifestyle and norms (Patarasuk et al., 2016; Porse et al., 2016), urban form and density (Baiocchi et al., 2015; Creutzig et al., 2015a; Karathodorou et al., 2010; Mindali et al., 2004; Newman and Kenworthy 1989, 1999), technology (Kennedy et al., 2009, 2014, 2015), and climate (Baiocchi et al., 2015; Creutzig et al., 2015a; Glaeser and Kahn 2010; Kennedy et al., 2015). Research continues to establish the relative permanence of large technological and infrastructural systems in urban areas. For example, fossil fuel–burning infrastructures have lifetimes up to 50 years, leading to systemic dependence (i.e., "lock-in") on fossil fuel–based technology (Unruh 2000; Seto et al., 2016; Erickson et al., 2015).

Major uncertainties

Increasing numbers of studies examine relationships between urban density and 1) atmospheric emissions and 2) building energy use. Uncertainty exists relative to the ability of cities to change their infrastructure because of cost considerations and municipal regulations, as well as state and national regulations that affect city form and infrastructure. Relationships among the core elements of carbon lock-in (i.e., technological, institutional, and behavioral) are poorly understood and involve interactions among scales of governance larger than urban areas. All these aspects vary widely across cities and North American countries.

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

Studies are emerging that investigate these relationships, but more research is needed to understand the processes.

Summary sentence or paragraph that integrates the above information

For Key Finding 2, cities are complex systems with a mix of societal factors driving carbon emissions. Uncertainties remain regarding a complete typology of driving factors and the extent to which these factors lead to path dependencies and the ability of urban areas to alter infrastructure and technological trajectories.

KEY FINDING 3

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

Description of evidence base

Key Finding 3 is supported by recent research that begins to integrate and reconcile carbon flux information from intensive urban study sites in North America. Key supporting references include Gurney et al. (2017), Lamb et al. (2016), Lauvaux et al. (2016), and McKain et al. (2012, 2015).

Major uncertainties

The major uncertainties related to integrating and reconciling urban carbon budget studies are those intrinsic to the different methodologies used. For trend detection and mitigation guidance, major uncertainties arise from the differences in scientific goals versus policy application.

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

There is broad agreement that integration and reconciliation remain challenging. However, the various disciplines that pursue different methodological approaches to urban carbon flux assessment have different 1) definitions of uncertainty, 2) needs for attribution, and 3) criteria for successful mitigation guidance. Hence, some disagreement exists over specific policy application and utility.

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

Continued integration and reconciliation of urban carbon fluxes are likely to achieve methodologically consistent and agreed-on approaches, results of which will be useful for trend detection and mitigation guidance. Assessment of enacted policy has received limited study, and thus the ability to independently assess atmospheric trends and use that information to inform mitigation progress and potential is highly important and relevant to urban carbon mitigation and climate policy.

Summary sentence or paragraph that integrates the above information

For Key Finding 3, the research community recently has begun to integrate and reconcile multiple approaches to urban carbon flux assessments for intensive study sites of urban carbon in North America. These efforts are ongoing but remain challenging due to methodological differences, methodological uncertainties, and differing disciplinary perspectives and criteria. The relevance and importance of these efforts are high because there remains limited independent assessment of urban carbon mitigation efforts or progress.

KEY FINDING 4

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

Description of evidence base

Numerous studies contribute to Key Finding 4, including research on the impacts of carbon emissions reductions on local air pollution, related human health benefits, and reduction of waste heat discharge (Harlan and Ruddell 2011; Huang et al., 2013; Jacobson and Ten Hoeve 2012; Milner et al., 2012; Ostro et al., 2011; Sarofim et al., 2016; Viguié and Hallegatte 2012).

Major uncertainties

Uncertainties include the precise magnitude of health and environmental benefits associated with reductions of carbon emissions. Benefits will vary with a number of factors such as urban population sociodemographics, urban meteorology, composition of emissions sources, and energy fuel mix. Tradeoffs require further research and remain uncertain.

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

There is broad agreement about the benefits of reducing carbon emissions. Major uncertainties are related to assessing quantitatively the impacts and precise relationships between carbon emissions reductions and urban health and environmental benefits.

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

Key Finding 4 is of high impact. The quantitative relationship between carbon emissions reductions and urban health and environmental impacts has direct and important implications for stakeholder decision making associated with urban air quality, urban climate policy, and general urban planning.

Summary sentence or paragraph that integrates the above information

For Key Finding 4, fossil fuel energy systems emit carbon dioxide (CO_2) and methane (CH_4). These systems also result in emissions of local air pollution and heat discharge in urban environments. Hence, reducing fossil fuel dependence can provide co-benefits to human health and environmental impacts associated with urban heat. The net benefit of these related outcomes remains uncertain because of potential tradeoffs and unforeseen outcomes.

KEY FINDING 5

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

Description of evidence base

For Key Finding 5, consistent and persistent evidence of under-reported CH_4 emissions was found in Los Angeles, Boston, and Indianapolis (Lamb et al., 2016; McKain et al., 2015; Wong et al., 2016). Other studies report inverted distributions of CH_4 emissions in Los Angeles (75% thermogenic, 20% biogenic; Hopkins et al., 2016) compared with San Francisco (17% thermogenic, 82% biogenic; Jeong et al., 2017). Intensive field surveys of urban natural gas systems in seven cities indicate large variations in CH_4 leakage rates from urban gas distribution infrastructure attributed to differences in pipeline material and age (Hopkins et al., 2016; Jackson et al., 2014; Phillips et al., 2013; von Fischer et al., 2017).

Major uncertainties

The uncertainties in urban-scale CH_4 emissions estimates are not well established because the number of cities where these emissions have been studied is small and the temporal duration of the studies is very limited. While Key Finding 5 is of high confidence for the limited times and numbers of cities represented in the literature, this finding cannot yet be generalized across other North American cities.

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

The assessment of confidence is based on a small number of cities where emissions have been studied over a short period of time. The confidence level is based on the results of these studies, which are robust and agreed upon, but this confidence does not necessarily apply across the continent due to the limited number of studies conducted to date.

Summary sentence or paragraph that integrates the above information

For Key Finding 5, urban CH_4 emissions estimates exist for several North American cities. Yet there are discrepancies between these estimates and governmental inventories. As such, further

research is needed to gain a complete understanding of uncertainties and assess the representativeness of these studies.

KEY FINDING 6

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

Description of evidence base

Thousands of North American cities have joined municipal networks to pursue co-benefits from climate mitigation measures, including benchmarking initiatives. However, many cities do not have authority to dictate fuel sources for their energy supply or for vehicles, nor they do control carbon inputs into products that come into cities. Evidence for Key Finding 6 indicates that municipal carbon emissions mitigation initiatives in the United States vary significantly among states. This variation suggests that state-level policies and characteristics may influence the propensity of cities in their borders (Krause 2011). Jurisdictional barriers that restrict decision making by municipalities may impede change because of a lack of authority over decision making (Tozer 2013).

Major uncertainties

Cities vary in extent and type of innovation, though the precise motivation lacks sufficient evidence to provide a clear understanding of the factors involved. In addition, each country has different governmental arrangements that affect city autonomy; even within states in the same country, these arrangements may vary.

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

Evidence of the importance of cities is supported by the large proportion of North American anthropogenic carbon emissions (see Key Finding 1). The evidence for the moderated influence over carbon emissions is supported by the mixture of political, economic, and social authority of cities over direct and indirect emissions sources.

Summary sentence or paragraph that integrates the above information

For Key Finding 6, cities are making policies to reduce their carbon emissions, but they also are constrained by many factors that can limit their authority. Moreover, cities vary widely among themselves. An understanding of the limitations in the ability of cities to mitigate their carbon emissions and why certain cities are more proactive than others is still to be developed.

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5 Agriculture

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KEY FINDINGS

1. Agricultural greenhouse gas (GHG) emissions in 2015 totaled 567 teragrams (Tg)[1] of carbon dioxide equivalent (CO_2e)[2] in the United States and 60 Tg CO_2e in Canada, not including land-use change; for Mexico, total agricultural GHG emissions were 80 Tg CO_2e in 2014 (not including land-use change) (*high confidence*). The major agricultural non-CO_2 emission sources were nitrous oxide (N_2O) from cropped and grazed soils and enteric methane (CH_4) from livestock (*very high confidence, very likely*).[3]

2. Agricultural regional carbon budgets and net emissions are directly affected by human decision making. Trends in food production and agricultural management, and thus carbon budgets, can fluctuate significantly with changes in global markets, diets, consumer demand, regional policies, and incentives (*very high confidence*).

3. Most cropland carbon stocks are in the soil, and cropland management practices can increase or decrease soil carbon stocks. Integration of practices that can increase soil carbon stocks include maintaining land cover with vegetation (especially deep-rooted perennials and cover crops), protecting the soil from erosion (using reduced or no tillage), and improving nutrient management. The magnitude and longevity of management-related carbon stock changes have strong environmental and regional differences, and they are subject to subsequent changes in management practices (*high confidence, likely*).

4. North America's growing population can achieve benefits such as reduced GHG emissions, lowered net global warming potential, increased water and air quality, reduced CH_4 flux in flooded or relatively anoxic systems, and increased food availability by optimizing nitrogen fertilizer management to sustain crop yields and reduce nitrogen losses to air and water (*high confidence, likely*).

5. Various strategies are available to mitigate livestock enteric and manure CH_4 emissions. Promising and readily applicable technologies can reduce enteric CH_4 emissions from ruminants by 20% to 30%. Other mitigation technologies can reduce manure CH_4 emissions by 30% to 50%, on average, and in some cases as much as 80%. Methane mitigation strategies have to be evaluated on a production-system scale to account for emission tradeoffs and co-benefits such as improved feed efficiency or productivity in livestock (*high confidence, likely*).

6. Projected climate change likely will increase CH_4 emissions from livestock manure management locations, but it will have a lesser impact on enteric CH_4 emissions (*high confidence*). Potential effects of climate change on agricultural soil carbon stocks are difficult to assess because they will vary according to the nature of the change, onsite ecosystem characteristics, production system, and management type (*high confidence*).

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

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[1] Excludes emissions related to land use, land-use change, and forestry activities.

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

[3] Estimated 95% confidence interval lower and upper uncertainty bounds for agricultural greenhouse gas emissions: –11% and +18% (CH_4 emissions from enteric fermentation) and –18% and +20% and –16% and +24% (CH_4 and N_2O emissions from manure management, respectively; U.S. EPA 2018).

5.1 Introduction and Historical Context

Agricultural production is a fundamental activity conducted on 45% of the U.S. land area, 55% of Mexico's land area, and 7% of Canada's land area (World Bank 2016). Because of this vast spatial extent and the strong role that land management plays in how agricultural ecosystems function, agricultural lands and activities represent a large portion of the North American carbon budget. Accordingly, improved quantification of the agricultural carbon cycle, new trends in agriculture, and added opportunities for emissions reductions provide a critical foundation for considering the relationships between agriculture and carbon cycling at local, regional, continental, and global scales. More than 145 countries have specifically included agriculture in their targets and actions for mitigating climate change (FAO 2016), and agriculture has featured particularly prominently in recent target and action commitments made by developing countries to reduce greenhouse gas (GHG) emissions (Richards et al., 2015).

Conversion of vast native forest and prairie to agriculture across North America between 1860 and 1960 resulted in carbon dioxide (CO_2) fluxes to the atmosphere from biota and soils that exceeded those from fossil fuel emissions over the same period (Houghton et al., 1983). Correspondingly, soil organic carbon (SOC) declined in many soils during the 50 years following conversion from native ecosystems to production agriculture (Huggins et al., 1998; Janzen et al., 1998; Slobodian et al., 2002). Crop yields and corresponding above- and belowground biomass have steadily increased since the 1930s due to genetic and management innovations, which provide more organic input from which to build SOC (Johnson et al., 2006; Hatfield and Walthall 2015). This, coupled with improved input-use efficiencies may reduce GHG-emissions per unit yield (GHG intensity), with additional improvements possible through management optimization (Grassini and Cassman 2012; Pittelkow et al., 2015). Options include reducing tillage, integrating perennials onto the landscape, reducing or eliminating bare-fallow land (i.e., land without living plants), adding cover crops, and enrolling lands in conservation easement programs. These options, originally proposed to control erosion, have potential co-benefits in terms of increased soil health, plant productivity, and soil carbon stabilization (Lehman et al., 2015). Conversely, returning lands previously enrolled in conservation easements (e.g., the Conservation Reserve Program [CRP] and other land set-aside efforts) to row-crop production, tillage, or aggressive harvesting of crop residues all risk degrading soil quality and exacerbating SOC loss. Of note is that the net results of land use and land management practices in an agricultural setting vary according to many factors, such as crop or production system type, soil type, climate, and the collection of practices at any given site. For example, many traditional practices followed by Indigenous people on tribal lands are based on an integrated approach to natural resource management and response to environmental change that may provide agricultural options uniquely suited to varied environmental settings (see Ch. 7: Tribal Lands, p. 303).

Agricultural land in the United States totaled 408.2 million hectares (ha) in 2014, of which 251 million ha were in permanent meadows and pastures, 152.2 million ha were in arable land, and 2.6 million ha were in permanent crops (FAOSTAT 2016). Compared with the distribution in 2007, these numbers reflect a 4.7 million ha decline in total agricultural lands, driven by declines in arable land and permanent crops but partially offset by a modest increase in permanent meadows and pastures. Although arable lands have been declining, the combined acreage of the four major crops (corn, wheat, soybeans, and cotton) has risen slightly, with increases in land planted in corn and soybeans and decreases in cotton and wheat (see Figure 5.1, p. 232). Despite the overall slight decline in agricultural land area, the value of U.S. agricultural production rose over the past decade as a result of increased production efficiency and higher prices (USDA 2017a; see also www.ers.usda.gov). Canada has about 65 million ha of agricultural land, of which

about 46 million ha are arable, accounting for only about 7% of the country's total land area (FAOSTAT 2017). Prominent crops on Canada's arable lands include cereals (e.g., wheat, barley, and maize), oilseeds (e.g., canola and soybeans), and pulses (e.g., peas and lentils). Natural and seeded pastures available for grazing in Canada make up about 20 million ha (Legesse et al., 2016). Agricultural land in Mexico makes up 107 million ha, of which 23 million ha are arable land, 2.7 million ha are permanent crops, and 81 million ha are permanent meadows and pastures (FAOSTAT 2017). Mexico's major crops are fruits, corn, grains, vegetables, and sugarcane.

5.2 Societal Drivers and Carbon Management Decisions

A number of social and economic factors drive CO_2 and other GHG emissions associated with agriculture (see Table 5.1, p. 233), including dietary preferences and traditions; domestic and global commodity markets; federal incentives for conservation programs; and technical capabilities for production, processing, and storage in different geographic regions. For example, policies and economic factors that influence bioenergy and biofuel feedstock production systems have diverse direct and indirect impacts on the carbon cycle as discussed later in this chapter and in Ch. 3: Energy Systems, p. 110. A biofuel's carbon footprint depends on the feedstock and its associated management as well as the efficiency of the eventual energy produced from the feedstock. Changes in the management of these social and economic factors can affect soil carbon sequestration and storage and agricultural GHG emissions. Another driver of changes in agricultural production systems is consumer demand for types of food (e.g., meat versus dairy versus vegetable) and provenance of food (e.g., grass-fed, organic, and local). Such influences can have both negative and positive effects on the carbon cycle in direct and indirect ways (see Box. 5.1, Food Waste and Carbon, p. 234). Decision support tools have been developed over the last decade to address agricultural impacts on climate and environmental drivers that play a role in the carbon cycle (for examples, see Ch.18: Carbon Cycle Science in Support of Decision Making, p. 728).

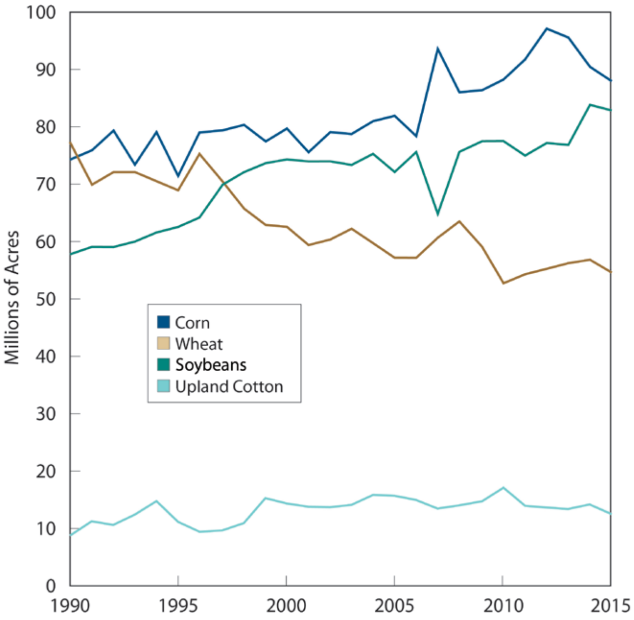

Figure 5.1. U.S. Planted Area for Corn, Wheat, Soybeans, and Upland Cotton, 1990 to 2015. (1 acre = 0.404686 hectares). [Figure source: Adapted from U.S. Department of Agriculture Economic Research Service, baseline related historical data.]

5.3 Current State of the Agricultural Carbon Cycle

Agricultural land carbon storage and loss are the net result of multiple fluxes including plant photosynthetic uptake (i.e., atmospheric CO_2 capture by plants), ecosystem respiratory loss (i.e., carbon released as CO_2 from plants and soil organisms), harvested biomass removal either by grazing or cutting, input from additional feeds, enteric methane (CH_4) production by livestock, and the return of manure by grazing animals or addition of manure or other carbon-rich fertilizer amendments to agricultural lands.

5.3.1 Perennial Systems

The most extensive perennial systems in North America are grasslands, pasture, and hayed lands (see Ch. 10: Grasslands, p. 399). Other perennial

Table 5.1. Greenhouse Gas Fluxes from North American Agriculture (Teragrams of Carbon Dioxide Equivalent per Year)

Emission Source	Canada[a]	United States[b]	Mexico[c]	Total by Source
Enteric Fermentation	25	166.5	43.3	234.8
Manure Management	8	84.0	25.7[f]	117.7
Agricultural Soil Management	24[d]	295.0	0	318.0
Rice Cultivation	0	12.3	0.2	12.5
Liming, Urea Application, and Others	3	8.7	7.5[g]	19.2
Field Burning of Agricultural Residues	0	0.4	1.3	1.7
Crop Residues	NR[e]	NR	1.9	1.9
Total by Country[h]	60	566.9	79.9	705.8

Notes

a) Source: ECCC (2018); data for 2016.
b) Source: U.S. EPA (2018); data for 2015.
c) Source: FAOSTAT (2017); average data for 1990–2014.
d) Includes emissions from field burning of agricultural residues.
e) Not reported.
f) Includes manure applied to soils, manure left on pasture, and manure management.
g) Synthetic fertilizer.
h) As reported in source; may not match sum of individual emission categories due to rounding.

crops (i.e., crops growing and harvested over multiple years) of regional importance include tree crops (mostly fruit and nuts) and vineyards. Because many perennial fruit, nut, and vegetable systems generally are intensively managed, the type of management—such as cover crops and intercropping, irrigation and tillage, fertilizer use, and intensity of cultural activities—largely determines the carbon balance of these production systems. Additionally, biofuel feedstock crops, including perennial grasses and short-rotation woody crops, occupy a very small percentage of agricultural land area, but they have the potential to either sequester carbon or create a carbon debt, depending on the system and land use that the system replaced (e.g., Adler et al., 2007, 2012; Mladenoff et al., 2016). Although differences in net carbon and GHG balance do exist, perennial bioenergy crops generally increase soil carbon in lands converted from annual crops because belowground carbon allocation (to roots) increases once the crops are established, even though the biomass is harvested for energy (Anderson-Teixeira et al., 2013; Valdez et al., 2017). However, managing perennials as biofuel crops often requires additional nitrogenous fertilizer, which can increase nitrous oxide (N_2O) emissions and reduce the associated mitigation potential (Johnson and Barbour 2016; see Ch. 3: Energy Systems, p. 110).

Perennial systems avoid the 4- to 8-month fallow period common among many annual row-crop systems (Drinkwater and Snapp 2007); therefore, perennial plants can use the sun's energy to drive photosynthesis outside the typical growing season (Baker and Griffis 2005), contributing to increased soil carbon sequestration as compared to annual systems (Sainju et al., 2014). In agricultural systems dominated by perennial plants, photosynthesis generally, but not always, exceeds ecosystem respiration, so on balance these ecosystems remove more CO_2 from the atmosphere than they contribute each year (Gilmanov et al., 2010). The total net amount of CO_2 exchanged between perennial systems and the atmosphere varies among regions, with net carbon loss occurring most often in drought-prone and desert systems (Liebig et al., 2012). In grazed ecosystems, better management practices, such as prescribed grazing, adaptive multipaddock grazing,

Box 5.1 Food Waste and Carbon

Over the past decade, several analyses have pointed to the magnitude of carbon and greenhouse gas (GHG) emissions associated with food waste and food choices and described opportunities to help minimize GHG emissions by reducing food waste, changing diets, and mitigating agricultural emissions (FAO 2013; Foley et al., 2011; Gunders 2012; Gustavsson et al., 2011; Hall et al., 2009; Heller and Keoleian 2015; Hristov et al., 2013b; Parfitt et al., 2010; Vermeulen et al., 2012). Globally, about 1,300 teragrams (Tg) of food per year, or one-third of food produced for human consumption, is lost or wasted. This loss represents production on about 1.4 billion hectares (ha) of land, roughly 30% of the global agricultural area (FAO 2013). On a per-person basis, food loss and waste in North America is 375 to 500 kilograms per year (FAO 2013; Garnett et al., 2013; Gustavsson et al., 2011; Heller and Keoleian 2015), and in the United States and Canada, most of the carbon lost to the atmosphere that is associated with this waste occurs during postprocessing (Bahadur et al., 2016; Porter et al., 2016; Smil 2012). Patterns of food waste in Mexico are less well documented. Public awareness; improved packaging techniques and materials; and improved coordination among producers, manufacturers, and retailers can reduce food waste and its associated carbon emissions (Garnett et al., 2013).

improved grass species and introduction of legumes, fertilization, and irrigation, generally will increase soil carbon sequestration (Conant et al., 2001; Teague et al., 2013). Estimates of the potential for U.S. pasture and hayed lands to sequester carbon (with improved management) vary, ranging from near 0 to 3 or more megagrams of carbon (Mg C) per hectare per year, with reasonable mean values of up to about 0.5 Mg C per hectare per year (Conant et al., 2001).

When productivity increases in agricultural systems, land managers frequently remove more aboveground biomass. In some cases, this increase in carbon removal by harvesting offsets the amount of carbon that would otherwise be sequestered, but the main driver of soil carbon sequestration is the production of belowground biomass that is not removed from the field. As a result, increased forage productivity often is associated with increased soil carbon sequestration (Allard et al., 2007; Ammann et al., 2007; Cong et al., 2014; Skinner and Dell 2016) because increased aboveground biomass normally is associated with increased belowground biomass. Initial conditions and ecosystem characteristics influence carbon sequestration potential. Depleted soils likely will accumulate additional carbon, whereas soils in which carbon inputs and outputs are roughly equal will show no change or perhaps a net loss of carbon over time (Smith 2004). Grazed pastures typically sequester more soil carbon than hayed land (Franzluebbers and Stuedemann 2009; Franzluebbers et al., 2000; Senapati et al., 2014) because cutting can cause a greater initial reduction and slower recovery in photosynthetic uptake of carbon than grazing (Skinner and Goslee 2016). Perennial root systems also become active early and remain active late in the growing season and thus can take up and use reactive nitrogen before it is lost from the system. The capture and efficient use of nitrogen (e.g., nitrate and ammonia applied at the correct time and rates) can avoid nitrogen losses. As a result, N_2O emissions for perennial systems are typically much lower than those for annual systems (Ma et al., 2000; Qin et al., 2004; Robertson and Vitousek 2009).

5.3.2 Annual Systems

As with perennial systems, carbon storage or loss in annually cropped lands is the net result of inputs from unharvested plant residue (especially below

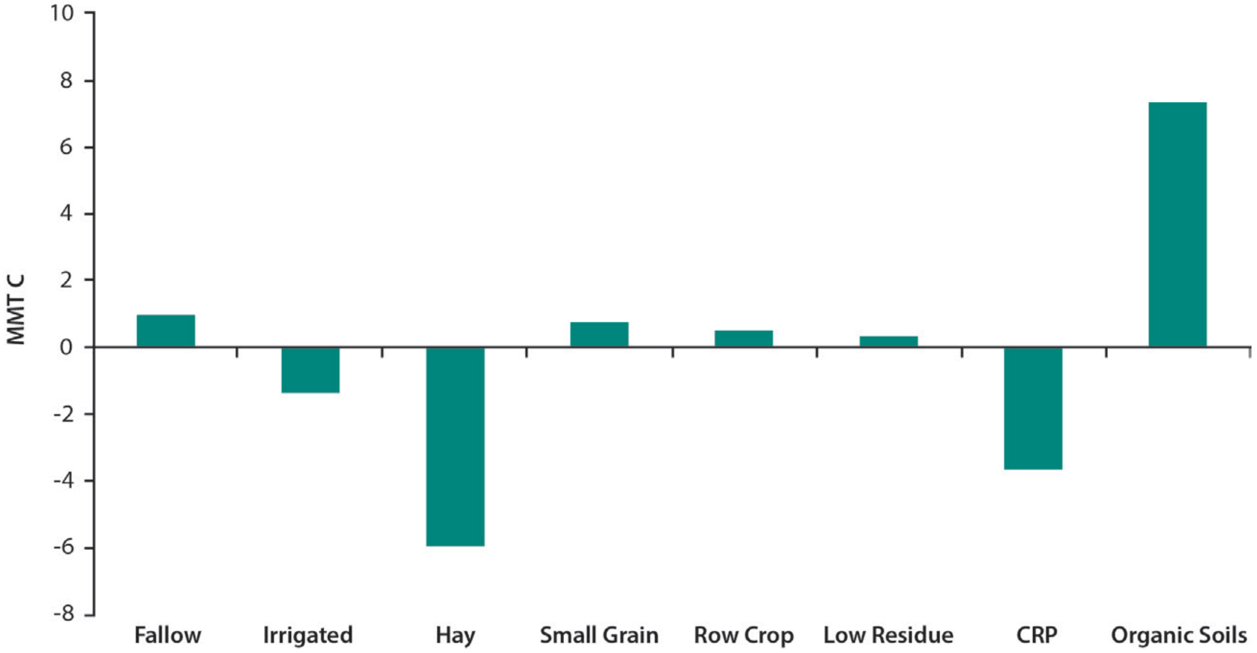

Figure 5.2. Soil Carbon Fluxes for Major Cropping Systems in the United States. Values, in million metric tons of carbon (MMT C), are annual means from 2003 to 2007. Positive values represent net carbon emissions from the system to the atmosphere, and negative values represent net carbon emissions from the atmosphere to system. Categories are mutually exclusive, and not all cropped land is included. Category definitions are based on the majority land use over the 5-year time period. For example, if a land parcel was cropped with maize or soybeans for at least 3 out of the 5 years, it was placed in the row-crop category. Similarly, if a land parcel was crop free during the growing season for at least 3 years, it was placed in the fallow category. Key: CRP, U.S. Department of Agriculture Conservation Reserve Program. [Data source: Del Grosso and Baranski 2016.]

ground); root exudation and turnover; organic matter deposition; soil amendments such as manure; and losses from respiration, residue, leaching, soil organic matter mineralization (decomposition), and harvested biomass removal. In turn, these input and output pathways respond to previous and current land use, soil properties (e.g., soil type and depth), climate, and other environmental factors. Typically, annual cropping systems are managed intensively; as such, their associated carbon stocks are closely related to land management choices (e.g., tillage, crop and crop rotation, residue management, fertilizer and nutrient inputs, extent and efficiency of drainage, and irrigation and use of cover crops) and the duration of those practices.

Studies to date suggest that annually cropped mineral soils in the United States sequester a small amount of carbon, but carbon emissions from cropped organic soils and a number of other farm management practices largely offset this benefit (Del Grosso and Baranski 2016; U.S. EPA 2016; see Figure 5.2, this page). Cropped organic soils (e.g., Histosols) comprise only a small portion (<1%) of overall U.S. cropland, but these organic soils can be a large source of atmospheric carbon on a per area basis. This carbon loss occurs because cropped organic soils commonly result from draining wetlands, which greatly enhances decomposition rates in these high-carbon soils that, historically, have been under water and relatively safe from decomposition. Reversion of these drained and cropped organic soils to wetlands or flooded rice production slows the soil carbon losses but also can result in increased CH_4 and N_2O emissions, implying that water management can play a key role in the

net carbon and GHG balances (Bird et al., 2003; Deverel et al., 2016; Oikawa et al., 2017). However, N_2O does not necessarily increase with land-use conversion to paddy rice because there is evidence of N_2O uptake by recently converted upland crops to flooded rice (Ye and Horwath 2016). Other practices that tend to lead to carbon loss include leaving land fallow without vegetation, growing low-residue crops (e.g., cotton), and plowing intensively (USDA 2014). Conversely, several practices may increase soil carbon stocks, such as including hay and grass in annual crop rotations, growing cover crops, maintaining plant cover, reducing the fallow (vegetation-free) period by increasing cropping intensity especially on marginal land as encouraged by CRP, and possibly reducing tillage intensity (USDA 2014). This increase in soil carbon stocks can vary by ecosystem but is particularly prevalent where these practices are used on soils previously depleted of their original carbon stores.

Compared to perennial crops, annual crop systems tend to have higher nitrogen losses, including N_2O emissions. In addition, nitrogen fertilizer additions generally lead to increased CH_4 emissions and decreased CH_4 oxidation from soils, particularly under anoxic conditions or flooded soil systems such as rice (Liu and Greaver 2009).

5.3.3 Livestock Systems

The North American livestock sector currently represents a significant source of GHG emissions, generating CO_2, CH_4, and N_2O throughout the production process. Livestock contributions to GHG emissions occur either directly (e.g., from enteric fermentation and manure management) or indirectly (e.g., from feed-production activities and conversion of forest into pasture or feed crops).

Enteric Fermentation

Methane and CO_2 are natural end-products of microbial fermentation of carbohydrates and, to a lesser extent, amino acids in the rumen of ruminant animals and the hindgut of all farm animals. Methane is produced in strictly anaerobic conditions by highly specialized methanogenic microbes. In ruminants, the vast majority of enteric CH_4 production occurs in the rumen (i.e., the largest compartment of the ruminants' complex stomach); rectal emissions account for about 3% of total enteric CH_4 emissions (Hristov et al., 2013b). Methanogenic microbes inhabit the digestive system of many monogastric and nonruminant herbivore animals (Jensen 1996). In these species, CH_4 is formed by processes like those occurring in the rumen and is similarly increased by intake of fibrous feeds. Summarizing published data, Jensen (1996) estimated that a 100-kg pig produces about 4.3% of the daily CH_4 emissions of a 500-kg cow. Nonruminant herbivore animals such as horses consume primarily fibrous feeds and emit greater amounts of CH_4 than nonruminant species that consume primarily nonfibrous diets, but a horse's CH_4 production per unit of body weight is still significantly less than that of ruminants. Wild animals, specifically ruminants (e.g., bison, elk, and deer), also emit CH_4 from enteric fermentation in their complex stomachs or the lower gut. The current contribution of wild ruminants to global GHG emissions is relatively low (Hristov 2012).

The U.S. Environmental Protection Agency (EPA) reports that CH_4 emissions from enteric fermentation and manure management amounted to about 232.8 teragrams (Tg) per year CO_2e (functionally equivalent to 63.5 Tg C) in 2015, with an additional 17.7 Tg per year CO_2e (4.8 Tg C) as N_2O emitted from manure management (U.S. EPA 2018). Combined, these emissions represented 3.8% of total U.S. GHG emissions. About 97% of the enteric fermentation and 57% of the CH_4 emissions from manure management were from beef and dairy cattle; 78% of the N_2O emissions from manure management also were attributed to beef and dairy cattle. These estimates are derived from a "bottom-up" approach that begins with estimates of emissions on a per-animal basis and multiplies those estimates over total relevant numbers of animals. "Top-down" approaches, based on measurements of changes in GHG concentrations over large areas and inferences about the sources of those changes, yield different estimates for CH_4 emissions. Combining

satellite data and modeling, several studies proposed that livestock emissions may range from 40% to 90% greater than EPA estimates (Miller et al., 2013; Wecht et al., 2014). There is more uncertainty in predicting CH_4 emissions from manure, partially because these emissions depend heavily on the particular manure handling system and temperature. The sources of discrepancy between the top-down and bottom-up approaches need to be identified to derive accurate estimates for both total and livestock CH_4 emissions in North America (NASEM 2018).

There is no disagreement, however, that cattle are a significant source of CH_4 emissions. Based on U.S. EPA (2018) estimates, CH_4 emissions from cattle make up 25.9% of total U.S. CH_4 emissions if only enteric emissions are counted, or 36.2% if emissions from manure management are included. In a national life cycle assessment of fluid milk, 72% of GHG emissions associated with milk production occurred on the farm, with 25% being from enteric CH_4 fermentation. The remaining 28% was associated with processing, packaging, distribution, retail, and consumers (Thoma et al., 2013). A similar life cycle assessment of beef indicates that 87% of GHG emissions associated with beef are from cattle production, with only 13% resulting from post-farm processes (Asem-Hiablie et al., 2018). Similar to ruminants, animal production is the main contributor of GHG emissions in the swine industry. A life cycle assessment of the U.S. pork industry (Thoma et al., 2011) reported the following breakdown of emission contributions for each stage of the production cycle: 9.6%, sow barn (including feed and manure management); 52.5%, nursery-to-finish (including feed and manure handling); 6.9%, processing (including 5.6% for processing and 1.3% for packaging); 7.5%, retail (e.g., electricity and refrigerants); and 23.5%, the consumer (e.g., refrigeration, cooking, and CH_4 from food waste in landfills). Major sources of GHG emissions in the poultry industry differ depending on the type of production. For broilers (i.e., meat-producing birds), feed production contributes 78% of the emissions; direct on-farm energy use, 8%; post-farm processing and transport of meat, 7%; and manure storage and processing, 6%. For layers (i.e., egg-producing birds), feed production contributes 69% of emissions; direct on-farm energy use, 4%; post-farm processing and transport, 6%; and manure storage and processing, 20% (MacLeod et al., 2013).

Manure Management

Manure can be a major source of GHG emissions, depending on the type of livestock. For ruminants, manure emissions normally are less than those from enteric production, but for nonruminants, manure is the major source of GHG emissions. Microbial activity breaks down organic carbon in manure, releasing both CH_4 and CO_2, and the amount of each produced is related to oxygen availability. Much of the carbon in manure eventually ends up in the atmosphere in one of these two forms, and because CH_4 is a more powerful GHG than CO_2, converting this biogenic carbon to CO_2 would be beneficial.

Methane emissions from all manure produced and handled in the United States were estimated to be 66.3 Tg CO_2e in 2015 (U.S. EPA 2018). These emissions occur in the housing facility, during long-term storage, and during field application (see Table 5.2, p. 238). The housing facility usually is a relatively small source. Manure lying on a barn floor or open-lot surface is exposed to aerobic conditions where CH_4 emissions are low (IPCC 2006; USDA-ARS 2016). Manure deposited by grazing animals also is exposed to aerobic conditions, with CH_4 emissions similar to those from a barn floor or open lot. When manure in the housing facility is allowed to accumulate in a bedded pack up to a meter deep, anaerobic conditions develop, leading to greater CH_4 emissions (IPCC 2006).

Long-term storage normally is the major source of carbon emissions from manure (see Table 5.2). Liquid or slurry manure typically is stored for 4 to 6 months prior to cropland application. During storage, anaerobic conditions are maintained in which CH_4 formation and emission rates are largely controlled by manure temperature (IPCC 2006; USDA-ARS 2016). Longer storage periods

Table 5.2. Estimated Methane Emissions from Livestock Manure Sources in the United States

Species	Portion Lost from Each Farm Source (%)[a]			Total Emissions[b] (Teragrams of Carbon Dioxide Equivalent)
	Housing Facility	Long-Term Storage	Field Application and Grazing	
Dairy Cattle	15 to 20	70 to 80	5 to 10	34.8
Swine	10 to 15	80 to 90	1	24.6
Poultry	45 to 55	45 to 55	1	3.4
Beef Cattle	10 to 15	15 to 20	60 to 70	3.1
Horses	5	35	60	0.2
All Other	5	35	60	0.1
Total	15 to 18	70 to 80	5 to 10	66.3

Notes

a) Estimated from emissions factors (IPCC 2006) and experience with the Integrated Farm System Model (USDA-ARS 2016) and assumed common manure management practices for each species.

b) From U.S. EPA (2018); 2015 emissions data.

will produce greater emissions. Manure solids can float to the surface, particularly in slurry manure, where a crust is formed. This natural crust can reduce storage CH_4 emissions by 30% to 40% (IPCC 2006; USDA-ARS 2016). Solid manure may be stored up to several months in a stack with or without active composting. This type of storage maintains more aerobic conditions, which reduce CH_4 emissions.

Following storage, manure typically is applied to cropland as a nutrient source for plant growth. During unloading from storage and field application, any CH_4 remaining in the manure is released. These emissions are small compared to those from other sources. Following application of the manure spread onto the soil in a thin layer, aerobic conditions suppress further CH_4 production. Manure also may be incorporated into the soil so that any CH_4 produced is oxidized and consumed (Le Mer and Roger 2001). Thus, optimizing the timing, quantity, and incorporation of manure applications with plant productivity and growth patterns and needs can reduce the associated CH_4 and N_2O emissions.

5.4 Indicators, Trends, and Feedbacks

5.4.1 Trends in Acres Cultivated, Soil Carbon, and Overall Emissions

The *First State of the Carbon Cycle Report* (CCSP 2007) showed total agricultural and grazing lands in North America (e.g., cropland, pasture, rangeland, shrub lands, and arid lands) accounting for 17% of global terrestrial carbon stocks. Most of this carbon pool existed within soils; less than 5% resided in cropland vegetation. More recent data estimate that the annual U.S. soil carbon sequestration rate decreased between 1990 and 2013, primarily due to changes in land use and variability in weather patterns. Worth noting are the large interannual fluctuations in the size of the mineral soil CO_2 sink (USDA 2016). The major non-CO_2 emissions from U.S. agriculture in 2013 were N_2O from cropped and grazed soils (44% of U.S N_2O emissions) and enteric CH_4 from livestock (28% of U.S. CH_4 emissions). In 2015, the major non-CO_2 emissions from U.S. agriculture were N_2O from agricultural soil management (52% of all agricultural emissions, or 4.4% of all U.S. GHG emissions) and enteric CH_4

from livestock (29% of agricultural emissions, or 2.5% of all U.S. GHG emissions). Combined with forestry, the agricultural sector contributed to a total net carbon sequestration of 270 Tg CO_2e in 2013 (USDA 2016), while total agricultural GHG emissions (excluding land use, land-use change, and forestry activities) amounted to 567 Tg CO_2e in 2015 (U.S. EPA 2018).

Agricultural GHG emissions in North America were 706 Tg CO_2e in 2014 and 2015 (Table 5.1, p. 233), including 567 Tg CO_2e in the United States (excluding emissions from land use, land-use change, and forestry; U.S. EPA 2018), 59.0 Tg CO_2e in Canada, and 79.9 Tg CO_2e in Mexico (Table 5.1). Agricultural non-CO_2 emissions were primarily N_2O from cropped and grazed soils and CH_4 from enteric fermentation in livestock. In 2014 and 2015, North America's major sources and annual rates of GHG emissions (in CO_2e) included: agricultural soil management (318.0 Tg), enteric fermentation (234.8 Tg), manure management (117.7 Tg), and rice cultivation (12.5 Tg; Table 5.1). Trends that drive North American GHG emissions from agriculture include changes in five areas: 1) the amount of nitrogen fertilizer applied, which correlates with land area planted in corn, cotton, and wheat (USDA 2016); 2) the number of ruminants, especially beef cattle and dairy cows because they produce large quantities of enteric and manure CH_4; 3) trends in human diet choices, which drive changes in land use, numbers of livestock, and volumes of inputs like fertilizer; 4) area of agricultural land opened by clearing forest, which converts large amounts of carbon in plants and soils to CO_2; and 5) the amount of food wasted, which leads to CH_4 emissions from landfills and also drives additional production with associated GHG emissions (e.g., Hall et al., 2009). Overall, actively managed agricultural lands have a strong capacity to reduce GHG emissions to the atmosphere and take up and store carbon. Varying management options thus could lead to substantial reductions in emitted CO_2 and CH_4 and sequester significant amounts of carbon.

According to the U.S. 2012 Agricultural Census, 370 million ha were classified as farmland (see Table 5.3, p. 240). Such lands declined by 3.1 million ha between 2007 and 2012 (USDA-NASS 2012). Out of the converted croplands, 18% changed to nonagricultural uses (e.g., urban growth and transportation); another 3% reverted to forest; and the remaining 79% were used for other types of agricultural land, primarily pastures (USDA-NRCS 2015). The conversion of farmland to other uses appears to have slowed compared with the period from 2002 to 2007, when greater than 9.6 million ha of farmland were converted to other uses (USDA-NASS 2012). In 2012, 19% of the total 786.8 million ha in the contiguous 48 states, Hawai‘i, Puerto Rico, and the U.S. Virgin Islands was classified as cropland, 1% as CRP, 6% as pastureland, and 21% as rangeland (USDA-NRCS 2015).

Similar to these trends in North America, global GHG emissions from large ruminants, such as beef and dairy cattle, are about seven times greater than emissions from swine or poultry (Gerber et al., 2012). Dairy production systems, however, are considerably more efficient than beef systems. As an example, Eshel et al. (2014) estimated, using a full life cycle assessment, that GHG emissions per human-edible megacalorie (MCal) were 9.6 kg CO_2e for beef versus 2 for pork, 1.71 for poultry, and 1.85 for dairy. Similarly, GHG emissions per kg of human-edible protein were 214 kg CO_2e for beef, 42 for pork, 20 for poultry, and 32 for dairy (Eshel et al., 2014).

U.S. cattle inventories have fluctuated during the last several decades from a peak of over 130 million heads (both beef and dairy) in the 1970s to a low of 88.5 million in 2014. Cattle numbers increased to 89 million in 2015 and an estimated 92 million in 2016 (USDA-NASS 2016). According to the 2016 inventory, there were 30.3 million beef cows, 9.3 million dairy cows, 19.8 million heifers weighing 227 kg or more, 16.3 million steers at 227 kg or more, 14 million calves under 227 kg, and 2.1 million bulls. Beef and dairy cows, because of their high feed consumption and higher-fiber diets, are the largest emitters of enteric CH_4, producing about 95 and

Table 5.3. United States Agricultural Lands by Sector and Percentage of Cropland Reportedly Managed with Conservation Practice and Distribution of Crops and Managements[a]

Land	Acreage (Million Hectares)	No Till (%)[b]	Other Conservation Tillage (%)	Cover Crop	Conservation Easement
Total Agricultural Lands 2012	370.1				
Cropland[c]	157.7	24	19.67	2.41	3.38
Pasture	49	NA[d]			
Rangeland (Includes Federal and Nonfederal Lands)	246.7				
Conservation Reserve Program	1.5				
Crop	**Acreage (Million Hectares)**	**Percentage of Cropland**	**Managed Under No Till or Strip Till (%)[e]**		
Corn	38.3	24.3	31		
Soybeans	30.8	19.5	46		
Wheat	19.8	12.6	33		
Cotton	3.8	2.4	43		
Sorghum	1.1	1.6	NA		
Rice	1.1	0.7	NA		
Hay[f]	22.8	14.4	NA		

Notes

a) The percentage of no-tilled land does not imply that these lands are managed in a long-term, no-till system.
b) Duration of no-till practice is not available; this value does not necessarily reflect a continuous practice.
c) USDA-NASS (2012).
d) Not applicable.
e) Wade et al. (2015).
f) USDA-NRCS (2015).

146 kg CH_4 per head per year, respectively; emissions from feedlot cattle fed high-grain diets are considerably less at 43 kg per year per head (U.S. EPA 2018). Increased cattle productivity has resulted in increased feed efficiency and decreased enteric CH_4 emission intensity (i.e., CH_4 emitted per unit of milk or meat). As an example, the estimated CH_4 emission intensity for the U.S. dairy herd has decreased from 31 g per kg milk in 1924 to 14 g per kg in 2015 (Global Research Alliance on Agricultural Greenhouse Gases 2015).

Cattle inventories in Canada have fluctuated annually, but long-term trends are relatively stable—about 12 million heads in January 2016, down slightly from a peak in 2005 (Statistics Canada 2016). Beef cattle account for more than 80% of these animals. In recent decades, improvements in management efficiency have led to a decline in GHG emissions per unit of livestock product. For example, estimated emissions per kilogram of liveweight beef leaving the farm declined from 14 kg CO_2e in 1981 to 12 kg CO_2e in 2011 (Legesse et al., 2016).

U.S. beef consumption has been declining steadily over the past decade (see Figure 5.3, p. 241) while consumption of dairy products has been increasing (see Figure 5.4, p. 242). The previously mentioned life cycle assessment analyses that found greater

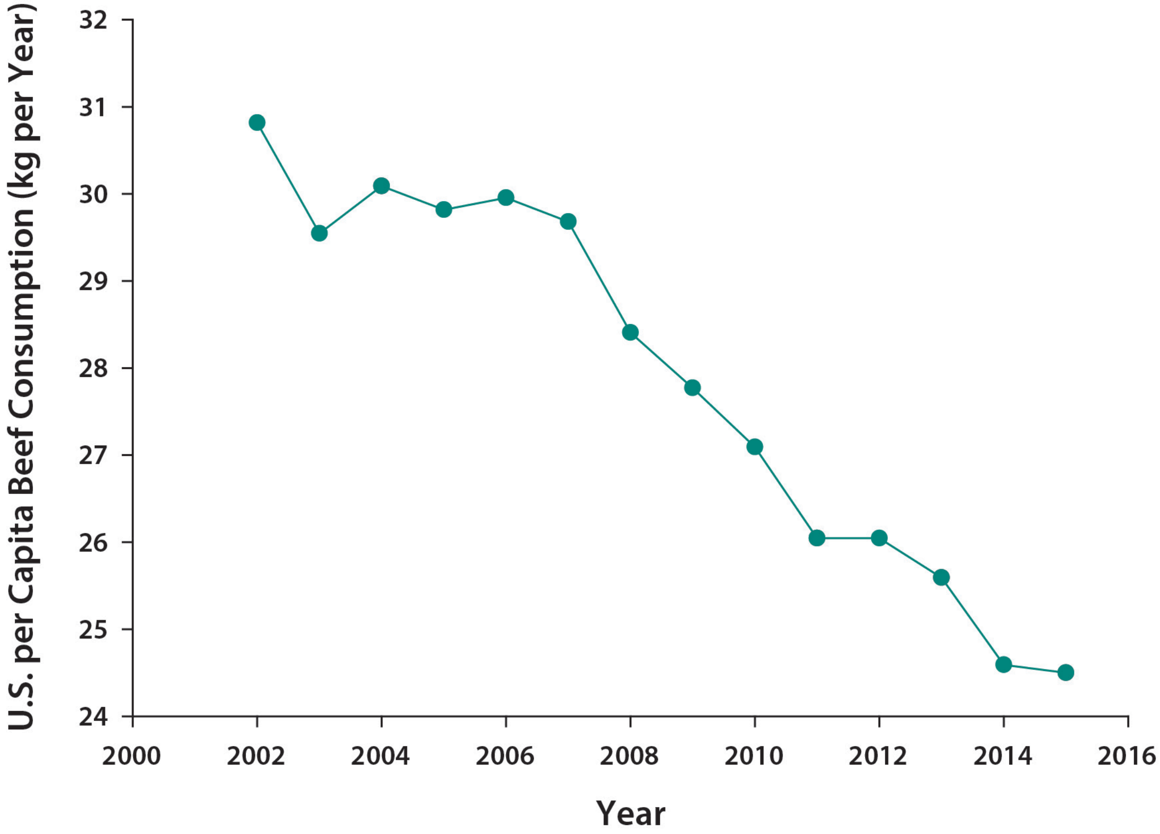

Figure 5.3. U.S. per Capita Beef Consumption. [Data sources: U.S. Department of Agriculture (USDA) National Agricultural Statistics Service and USDA Economic Research Service.]

carbon efficiency of dairy versus beef suggest that this trend should translate to lower emissions from the livestock sector. Most of the beef and veal consumed in the United States was domestically produced (about 86% in 2015; 18.6% of imported beef was from Canada), while about 9.6% of beef produced in the United States in 2015 was exported to other countries. Fluid milk consumption per capita has been decreasing—from about 89 kg per year in 2000 to 71 kg per year in 2015, while consumption of cheese, butter, and yogurt, most of which is domestically produced, has been steadily increasing. As in the United States, per capita consumption of livestock products in Canada also has declined in recent decades. For example, beef and fluid milk consumption decreased from 39 kg of beef per capita in 1980 to 24 kg in 2015 (Agriculture and Agri-Food Canada 2016) and from 90 liters of fluid milk per capita in 1996 to 71 liters in 2015 (Government of Canada 2016).

The strong influence of these carbon-intensive food consumption patterns on the global carbon cycle highlights the challenge of assigning emissions to a particular country. As mentioned previously, 2.5% of beef consumed in the United States is imported from Canada. Most inventories assign these emissions to the country where production occurs, but a main lever that could influence GHG emissions associated with this production rests, in this case, with the United States, because demand is a strong driver of supply and production.

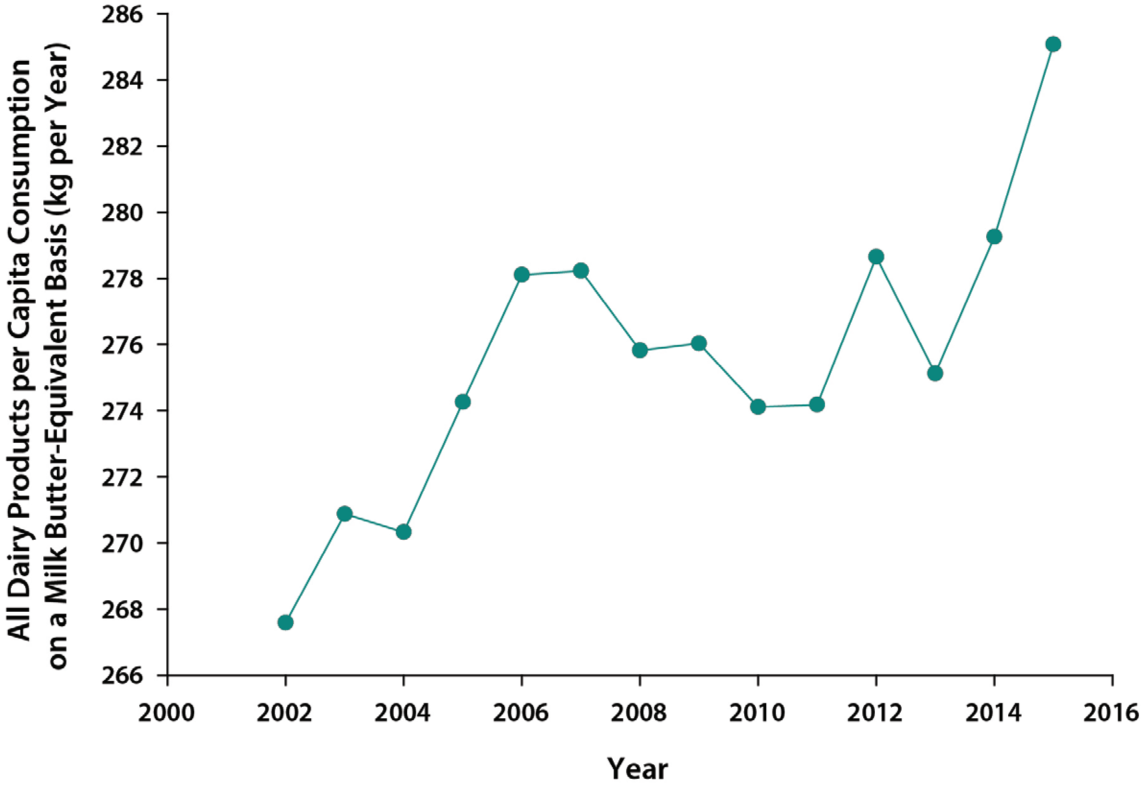

Figure 5.4. U.S. per Capita Total Consumption of Dairy Products. [Data sources: U.S. Department of Agriculture (USDA) National Agricultural Statistics Service and USDA Economic Research Service.]

5.4.2 Climate Change Effects and Feedbacks on Carbon

Climate change, including changes in temperature, precipitation, and the frequency of extreme events, could alter the productivity of agricultural systems through its effects on plant and animal growth as well as carbon sequestration and storage by influencing soil respiration and plant allocation to soil carbon. Climate change also could have an indirect effect on enteric CH_4 emissions (i.e., from ruminant animals) and directly influence manure and soil-derived CH_4 emissions through temperature increases. The effect on enteric emissions is through increased or decreased feed (i.e., dry matter) intake; projected increased ambient temperatures can decrease dry matter intake and thus proportionally reduce enteric CH_4 emissions. As an example, the average maximum temperature for the northeastern United States is projected to increase 6.5°C by 2100 (projected by Representative Concentration Pathway 8.5, a high-emissions scenario). This temperature increase is expected to decrease dry matter intake of dairy cows in the region by an additional 0.9 kg per day due to heat stress (Hristov et al., 2017a). This decreased intake will amount to a reduction in daily enteric CH_4 emissions of about 17 g per cow. If this reduction is extrapolated over 365 days and 1.4 million cows in the northeastern United States, the increased temperature will lead to a decrease in enteric CH_4 emissions from dairy cows of about 8.7 metric tons per year, but the net effect on CO_2e per kg of product depends on the effect of temperature on productivity. In contrast, increased temperatures are expected to increase manure CH_4 emissions. The microbial decomposition of manure, producing

CH_4, is sensitive to temperature, so the projected climate changes suggest an increase in emissions of about 4% by midcentury and 8% by 2100 (Rotz et al., 2016).

Climate change effects on soil carbon sequestration will involve a balancing act between the impacts of elevated CO_2, higher temperatures, and either increasing or decreasing precipitation depending on the region under consideration. Elevated CO_2 and increased precipitation are expected to increase carbon inputs into systems and increase their potential to sequester carbon, whereas higher temperatures are expected to increase ecosystem respiration. Also, yields of major crops (corn, soybeans, wheat, and rice) are predicted to decline as global temperature increases (Zhao et al., 2017). Reduced precipitation or soil moisture along with the drying effects of warming would be expected to decrease plant production and carbon inputs in most upland systems. In unmanaged ecosystems, limited nitrogen availability could constrain the positive effects of elevated CO_2 on plant growth (Norby et al., 2010; Thornton et al., 2007), although in managed pasture and hayland systems, fertilization would be expected to overcome such constraints. Tubiello et al. (2007) suggested that the balance between competing pressures would result in greater crop yields in temperate regions compared with those in semiarid and tropical regions. However, several analyses suggest that increased atmospheric CO_2 will increase soil CO_2 respiration by almost as much as the stimulation of inputs, resulting in little net change in soil carbon pools (Dieleman et al., 2012; Todd-Brown et al., 2014; van Groenigen et al., 2014). Because the potential effects of climate on soil carbon sequestration could be relatively small in most North American agricultural systems, at least compared with the large changes expected in the Arctic (Todd-Brown et al., 2014; see Ch. 11: Arctic and Boreal Carbon, p. 428), management is projected to have a greater effect on carbon sequestration than will changes in climate (Álvaro-Fuentes and Paustian 2011; Lugato and Berti 2008).

5.5 Agriculture's Impact on Atmospheric CO_2

The 2018 EPA inventory (U.S. EPA 2018) attributed 567 Tg CO_2e to the agricultural sector for 2015 (excluding emissions related to land use, land-use change, and forestry activities), accounting for 8.5% of total U.S. emissions.[4] This proportion reflects a small increase since 1990, primarily due to increased CH_4 emissions from manure management. Nitrous oxide emissions from agricultural soil management were the largest sources of GHGs at 295 Tg CO_2e, and these emissions, largely due to synthetic nitrogen fertilizer applications, accounted for 77.7% of all U.S. N_2O emissions. Other sources primarily included enteric fermentation (166.5 Tg CO_2e), manure management (66.3 Tg CO_2e and 17.7 Tg CO_2e as CH_4 and N_2O, respectively), rice cultivation (12.3 Tg CO_2e), field burning (0.4 Tg CO_2e), and CO_2 emissions from urea fertilization and liming (4.9 and 3.8 Tg CO_2e, respectively). Within the enteric fermentation emissions, beef cattle accounted for 70.9% and dairy cattle 25.6%. Worth noting is that these numbers have been relatively stable since 1990 even though production of beef and dairy products has increased. Agricultural croplands remaining as cropland in the United States (i.e., not converted to or from other land uses) represent a small sink sequestering an estimated 0.1% of the CO_{2e} removed from the atmosphere by land use, land-use change, and forestry activities (U.S. EPA 2018). As noted previously, agricultural practices that remove CO_2 from the atmosphere include conversion from cropland to permanent pastures or hay production, reduction in acreage managed with summer fallow, adoption of conservation tillage practices, and increased applications of manure or sewage sludge. Overall, SOC increases in croplands remaining cropland and croplands converted to grasslands collectively offset losses caused by recent conversions of long-term grassland to cropland

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[4] Estimated 95% confidence interval lower and upper uncertainty bounds for agricultural GHG emissions: –11% and +18% (CH_4 emissions from enteric fermentation) and –18% and +20% and –16% and +24% (CH_4 and N_2O emissions from manure management, respectively; U.S. EPA 2018).

(U.S. EPA 2015, 2016, 2018; see also Ch. 12: Soils, Section 12.5.1, p. 484).

In Canada, agricultural soils (55.2 million ha) contain about 4.1 petagrams (Pg) C (0- to 30-cm soil depth) and 5.5 Pg C (0- to 100-cm soil depth), as calculated from the Canadian Soil Information Service National Soil Database and reported in Ch. 12: Soils, p. 469. As of 2013, Canadian agricultural land removed 11 Tg CO_2 per year, which would counter about 2% of the total Canadian national GHG emissions (ECCC 2018). The reduction was attributed to decreased summer fallow and increased adoption of no-till practices in Canadian prairies. However, this value is starting to decline (e.g., down from 13 Tg CO_2 in 2005) because changes in SOC stocks and fluxes tend to approach equilibrium at some point after a change in conditions.

5.5.1 Impact of Management Practices

Croplands

Most cropland carbon stocks are in the soil and reflect management history and practices that increase or decrease soil carbon stocks. Integration of practices that can increase soil carbon stocks include 1) maintaining land cover with vegetation (e.g., use of deep-rooted perennials, elimination of summer fallow, and inclusion of cover crops in annual systems); 2) protecting the soil from erosion (e.g., reduced or no tillage and residue cover); and 3) improving nutrient management (Srinivasarao et al., 2015; Swan et al., 2015). The magnitude and longevity of carbon stock changes have strong environmental and regional differences that are subject to subsequent changes in management practices. Conversely, practices that convert lands from perennial systems, such as converting retired or other lands to row crops, consistently show release of stored carbon back to the atmosphere (Gelfand et al., 2011; Huang et al., 2002). Other management practices with the potential to release stored carbon are inadequate return of crop residues (e.g., Blanco-Canqui and Lal 2009), aggressive tillage (Conant et al., 2007), over application of nitrogen fertilizer, and burning of crop residue (Robertson and Grace 2004; Wang et al., 2011).

The timescale for carbon storage in soils is a critical factor for GHG mitigation. Numerous estimates of the rates and potential magnitude of long-term soil carbon accumulation, storage, and sequestration related to management have been reviewed and presented (e.g., Minasny et al., 2017; Paustian et al., 2016; Sperow 2016; Stockmann et al., 2013; Swan et al., 2015). Management practices that increase carbon inputs include planting high-residue crops and returning crop biomass to the soil; minimizing or eliminating summer fallow (particularly bare fallow); adding cover crops to reduce winter fallow; extending and intensifying cropping rotations (e.g., double-cropping or relay cropping and adding forage perennials); retiring marginal lands to perennials; and adding perennials in buffer strips, field borders, filter strips, grassed waterways, vegetative barriers, and herbaceous wind barriers (e.g., Mosier et al., 2006; Paustian et al., 2016; Sainju et al., 2010; Sperow 2016). Swan et al. (2015) estimated carbon storage rates of 0.42 to 0.95 Mg C per hectare per year among conservation practices that shift to perennials (e.g., retiring marginal land or planting perennials as barriers or borders), while inclusion of cover crops was estimated to accrue 0.15 to 0.27 Mg C per hectare per year. Practices that eliminate summer fallow can increase SOC directly by increasing carbon input or modifying microclimate (i.e., temperature and water), a practice that can decrease mineralization rates by reducing temperature and water content (Halvorson et al., 2002; Sainju et al., 2015).

Numerous publications have reported that no-tillage practices store more carbon in soil than those using conventional tillage (e.g., Paustian et al., 2016; Sperow 2016; West and Post 2002). Conversely, others have disputed this claim, especially when including soil carbon measurements deeper than 30 cm (e.g., Baker et al., 2007; Luo et al., 2010; Powlson et al., 2014; Ugarte et al., 2014). No-tillage and other conservation practices were developed to control soil erosion, and this co-benefit is well established. Erosion removes soil carbon from farm fields and relocates that carbon to other parts of the landscape; the amount of this transported carbon that is sequestered in sediments compared to the amount converted to CO_2 or CH_4 is difficult to

estimate (Doetterl et al., 2016). In Ch. 12: Soils, the role of soil erosion is discussed in greater detail and suggests that burial of eroded carbon constitutes a small sink. Comparing SOC sequestration rates from a system managed without tillage to a system with tillage results in negative, neutral, and positive rates of SOC sequestration: 1) 27 ± 19 Mg SOC per hectare per year, (n = 49; Liebig et al., 2005), 2) 0.40 ± 61 Mg SOC per hectare per year (n = 44; Johnson et al., 2005), or 0.45 ± 0.04 Mg SOC per hectare per year (n = 147; Franzluebbers 2010). Likewise, studies using eddy covariance techniques report divergent responses to tillage. For example, Bernacchi et al. (2005) demonstrated that no-tillage agriculture on clay-rich soil built SOC, whereas others (Baker and Griffis 2005; Chi et al., 2016; Verma et al., 2005) used gas exchange techniques to suggest conservation or no-tillage systems were near carbon neutral. In another review, Collins et al. (2012) found that carbon sequestration rates varied from no measurable increase (Staben et al., 1997) to 4 Mg C per hectare per year (Lee et al., 2007), varying with depth monitored, study duration, fertilizer formulation, and location. Several rationales have been postulated for this variability. If sampling depth is shallower than the tillage depth, the apparent change in SOC may be an artifact of sampling depth (Baker et al., 2007) or caused by residue redistribution (Staricka et al., 1991) and vertical stratification of soil carbon (Luo et al., 2010). Meta-analyses by Luo et al. (2010) and Ugarte et al. (2014) suggest that other factors contributing to variability in SOC sequestration include climatic and soil properties interacting with management factors (e.g., cropping frequency, crop rotation diversity, nitrogen, and drainage) along with impacts on rooting depth and above- and belowground biomass, as well as soil heterogeneity and the long time frames required to find a definitive increase or decrease in SOC. Collectively, the evidence indicates that adoption of no tillage may store more carbon, especially in the soil surface, compared to storage with conventional tillage. However, conclusively measuring short-term changes is difficult because of soil heterogeneity and slow rates of change (also discussed in Ch. 12: Soils). In particular, increased N_2O or CH_4 emissions have been shown to occur for as many as 10 years after no-till adoption (Six et al., 2004), though this effect is greater and more consistent in medium to poorly drained soils (Rochette 2008). Thus, quantifying GHG mitigation by management also must account for changes in N_2O and CH_4, which can occur coincidently with changes in soil carbon storage (VandenBygaart 2016).

From a carbon emissions perspective, biofuels have received a great deal of attention because of their potential to produce a more carbon neutral liquid fuel relative to fossil fuels. Biofuels from annual crops currently supply about 5% of U.S. energy use, mostly from corn grain ethanol (~36% of the corn grain harvest) and soy biodiesel (~25 % of the soybean harvest; USDA 2017b). Although the potential for reduced GHG emissions with biofuels is compelling, some life cycle assessment analyses suggest that corn grain ethanol has marginally lower (or even greater) GHG emissions compared with those from fossil fuels (e.g., Del Grosso et al., 2014; Fargione et al., 2008). However, more recent studies suggest that currently available technologies can achieve greater GHG reductions of 27% to 43% compared to gasoline when assessed on an energy equivalent basis (Canter et al., 2015; Flugge et al., 2017). Reasons for reduced net GHG intensity for grain- and oil-based biofuels include improved crop-management practices and diminished emissions from land-use change because most of the yield gap from diverting food and feed crops to biofuel feedstocks has been met by increasing per-unit area yields, taking into account the benefits of co-products (e.g., using dried distiller grains for livestock feed) and implementing more efficient feedstock conversion technologies (Flugge et al., 2017). Typically, cellulosic biomass conversion technologies are considered too expensive to compete with liquid fuels derived from other sources (Winchester and Reilly 2015), but innovations at all levels are advancing conversion technology. The impact of cellulosic biofuels on the carbon cycle (Fulton et al., 2015) will depend on ensuring that appropriate mitigation strategies are followed

during feedstock choice (perennial or annual) and cultivation (e.g., related to soil carbon stock changes [Blanco-Canqui 2013; Johnson et al., 2012, 2014; Qin et al., 2015]), transportation, and conversion to biofuels (U.S. DOE 2016).

Co-Benefits of Conservation Management

Many common conservation practices improve soil aeration, aggregate stability, and nutrient reserves, while modulating temperature and water and increasing microbial activity and diversity. As a result, soil under some conservation-management regimes can be more resilient to climate variability and more productive (Lal 2015; Lehman et al., 2015). For example, adoption of practices that can conserve soil carbon (e.g., perennial crops, cover crops, and no tillage) may reverse the effects of tillage-intense systems associated with environmental and soil degradation (Mazzoncini et al., 2011). Plant material maintained on the soil surface improves soil physical properties (e.g., Johnson et al., 2016), nutrient availability, and microbial biomass and activity (Feng et al., 2003; Weyers et al., 2013). These improvements result in enhanced soil and water quality and soil productivity (Franzluebbers 2008). Cover crops improve soil health by increasing microbial diversity, biomass, and activity (Bronick and Lal 2005; Lehman et al., 2012, 2015; Schutter and Dick 2002); they also improve soil aggregation, water retention, and nutrient cycling (Blanco-Canqui et al., 2013; Drinkwater et al., 1998; Kladivko et al., 2014; Liebig et al., 2005; Sainju et al., 2006). Thus, there are management practices that simultaneously benefit a number of soil health and carbon storage attributes.

5.5.2 Emissions Reduction

Livestock

Enteric fermentation and manure management represent 44% of the 2015 agricultural GHG emissions in the United States (U.S. EPA 2018) and 36% and 58% of the agricultural emissions in Canada and Mexico, respectively (FAOSTAT 2017). Of the total U.S. GHG emissions in 2015, however, emissions from enteric fermentation and manure management made up only 3.8% (U.S. EPA 2018). Methane mitigation practices for livestock include practices related to reducing emissions from enteric fermentation (i.e., cattle) and manure management (i.e., cattle and swine) as discussed by Hristov et al. (2013b) and Herrero et al. (2016). Increasing forage digestibility and digestible forage intake generally will reduce CH_4 emissions from rumen fermentation (and stored manure) when scaled per unit of animal product. Enteric CH_4 emissions may be reduced when corn silage replaces grass silage in the diet. Legume silages also may have an advantage over grass silage because of their lower fiber content and the additional benefit of reducing or replacing inorganic nitrogen fertilizer use. Dietary lipids are effective in reducing enteric CH_4 emissions, but the applicability of this practice will depend on its cost and effects on feed intake, production, and milk composition in dairy cows. Inclusion of concentrate feeds in the diet of ruminants likely will decrease enteric CH_4 emissions per unit of animal product, particularly when the inclusion is above 40% of dry matter intake.

A number of feed additives, such as nitrates, also can effectively decrease enteric CH_4 emissions in ruminants. Because these additives can be toxic to the animals, proper adaptation is critical. However, nitrates may slightly increase N_2O emissions, which decreases their overall mitigating effect by 10% to 15% (Petersen et al., 2015). Through their effect on feed efficiency, ionophores are likely to have a moderate CH_4-mitigating effect in ruminants fed high-grain or grain-forage diets. Some direct-fed microbial products, such as live yeast or yeast culture, might have a moderate CH_4-mitigating effect by increasing animal productivity and feed efficiency, but the effect is expected to be inconsistent. Vaccines against rumen methanogens may offer mitigation opportunities in the future, but the extent of CH_4 reduction appears small, and adaptation and persistence of the effect are unknown. A recently discovered enteric CH_4 inhibitor, 3-nitrooxypropanol, has shown promising results with both beef and dairy cattle. Under industry-relevant conditions, the inhibitor persistently decreased enteric CH_4 emissions by 30% in dairy cows, without negatively affecting animal

productivity (Hristov et al., 2015). Similar or even greater mitigation potential has been reported for beef cattle (Romero-Perez et al., 2015). If its effectiveness is proven in long-term studies, this mitigation practice could lead to a substantial reduction of enteric CH_4 emissions from the ruminant livestock sector.

Animal management also can have an impact on the intensity (i.e., emissions per unit of animal product) of CH_4 emissions from livestock systems. For example, increasing animal productivity through genetic selection for feed efficiency can be an effective strategy for reducing CH_4 emission intensity. Other management practices for significantly decreasing total GHG emissions in beef and other meat production systems include reducing age at slaughter of finished cattle and the number of days that animals consume feed in the feedlot. Improved animal health, reduced mortality and morbidity, and improved reproductive performance also can increase herd productivity and reduce GHG emission intensity in livestock production (Hristov et al., 2013a).

Several practices are known to reduce CH_4 emissions from manure but cannot be considered in isolation of other GHG sources and pollutants such as N_2O and ammonia (NH_3). Practices such as the use of solid manure storage and composting can reduce CH_4 emissions, but N_2O and NH_3 emissions will increase, and the end result may not be a reduction in overall GHG emissions. Mitigation of carbon emissions also may have tradeoffs with other pollutants including other gaseous emissions, nutrient leaching to groundwater, and nutrient runoff to surface waters. For example, eliminating long-term manure storage can greatly reduce CH_4 emissions, but daily spreading of manure throughout the year can cause greater nutrient runoff. Mitigation strategies must be considered from a whole-farm perspective to ensure a net environmental benefit (Montes et al., 2013).

Potential CH_4 mitigation strategies include manure solids separation, aeration, acidification, biofiltration, composting, and anaerobic digestion (Montes et al., 2013). Removal of solids from liquid manure reduces available carbon for methanogenesis, and composting or storing the solids in a stack under more aerobic conditions reduces total CH_4 emissions. For long-term manure storage, covers likely will become mandatory to reduce NH_3, CH_4, and N_2O emissions. Semipermeable covers such as the natural crust on slurry manure or added floating materials such as straw, wood chips, expanded clay pellets, and some types of plastic can reduce CH_4 and NH_3 emissions from storage by 30% to 80%, but they also may increase N_2O emissions. Greater reductions and perhaps near elimination of emissions can be achieved by sealing the cover and using a flare to convert the accumulated CH_4 to CO_2. Anaerobic digesters also can be used to enhance CH_4 production, capturing the produced biogas and using it on the farm to heat water and generate electricity. Extracting the carbon from manure reduces storage emissions, and the reduction in purchased gas and electricity provides other off-farm environmental benefits. Composting solid manure in aerated windrows can greatly reduce CH_4 emissions, but this processing will increase NH_3 and N_2O emissions (Montes et al., 2013).

Experimental processes of acidification and biofiltration show potential for reducing CH_4 emissions if practical and economical systems can be developed (Montes et al., 2013). Decreasing the pH of manure reduces NH_3 and CH_4 emissions, but the cost of the acid, safety in handling, and difficulty in maintaining the low pH all deter its use. Biofiltration can extract CH_4 from ventilation air in barns, but the large size and cost preclude adoption. Biofilters also may create N_2O emissions, offsetting some of the carbon reduction benefits.

Rice Production

Rice emits four to five times more CH_4 and N_2O to the atmosphere (Linquist et al., 2012) and uses two to three times more water per kg than other cereals (Bouman et al., 2007; Tuong et al., 2005). Sustainably oriented production practices have been developed with the goal of mitigating the environmental impact of rice and improving the economic benefits through reductions in production costs. These practices include the irrigation management practice of alternate wetting and drying (AWD) or intermittent

flooding, whereby the soil surface is allowed to dry for several days to a week before rewetting in midseason. This practice can be repeated up to five times during the growing season without reducing harvest yield. The concurrent re-oxygenation of the soil layer keeps CH_4 emissions low, and studies have shown that water-saving irrigation methods such as AWD reduce net CH_4 emissions produced under water-saturated conditions (Linquist et al., 2015; Rogers et al., 2013). Even one 6-day, midseason drainage event, temporarily reducing anaerobic soil conditions, can reduce post-drainage CH_4 emissions by 64% with no evident effect on yield (Sigren et al., 1997). This practice also has the co-benefit of reducing grain arsenic concentrations because it changes the soil reduction-oxidation (redox) potential (Linquist et al., 2015). Other irrigation techniques that reduce the inundated soil period also will reduce the CH_4 emissions from rice paddies. These methods include the use of drill-seeding rather than water-seeding or transplanting rice (Pittelkow et al., 2014) and carry the additional benefit of reducing the pumping requirements of irrigation water; thus, they will reduce GHG production associated with the energy use of burning fossil fuels—whether through diesel or indirectly through electricity generation. The reduced pumping benefits are particularly true in rice production regions of the Midsouth that are distinct from those in California, where irrigation needs are met from gravity-fed reservoirs draining the Sierra Nevada mountains. However, for any CH_4-reducing rice production regime, care must be taken to keep N_2O emissions low. As indicated, rates of N_2O emissions are particularly sensitive to inputs from nitrogen fertilization, fallow-season field conditions, and midseason or season-end drainage events (Pittelkow et al., 2013). In many cases, both CH_4 and N_2O are released in any drainage event, with end-of-season drainage transferring 10% of seasonal CH_4 and 27% of seasonal N_2O to the atmosphere as entrapped gases are released from the soil.

5.6 Global Context

Between 1960 and 2000, global crop net primary production (NPP) more than doubled, and global cropland area in 2011 was estimated to be 1.3 billion ha (Wolf et al., 2015). Global crop NPP in 2011 was estimated at 5.25 Pg C, of which 2.05 Pg was harvested and respired offsite (Wolf et al., 2015). Global livestock feed intake was 2.42 Pg C, of which 52% was grazed and the rest was either harvested biomass or residue collected from croplands. Global human food intake was 0.57 Pg C in 2011 (Wolf et al., 2015). The global agricultural carbon budget indicates a general increase in NPP, harvested biomass, and movement of carbon among global regions. At the global scale, cereal crops declined and have been replaced primarily with corn, soybean, and oil crops. While total NPP and yield (i.e., biomass per area) have increased in nearly all global regions since 1960, the most pronounced increase has been in southern and eastern Asia where harvested biomass has tripled. Also, cropland NPP in the former Soviet Union significantly declined in 1991, with the level of production recovering around 2010 (Wolf et al., 2015).

Annual crop cultivation and crop burning often is considered carbon neutral (IPCC 2006; U.S. EPA 2018) because biomass is harvested and regrown annually. Although biomass itself is technically carbon neutral, this assumption does not necessarily account for changes in soil carbon that may be associated with production practices, which affect the carbon cycle and net emissions. The impact of non-CO_2 emissions is accounted for in the other categories. The increased global uptake of carbon by croplands influences the annual oscillation of global atmospheric carbon (Gray et al., 2014), as more carbon is taken up and released annually than would occur without extensive global cropland production. The cycling of cropland biomass into soils and the cultivation of soils influence how much of the carbon in crop biomass is respired back to the atmosphere versus remaining in the soil, ultimately determining if a cropping system is a net source or sink.

5.7 Synthesis, Knowledge Gaps, and Outlook

5.7.1 Inventory Uncertainties

As previously discussed, enteric and manure fermentation are the sources of livestock CH_4 emissions. These two sources are affected by different factors

and carry different levels of uncertainties. The U.S. EPA estimated 95% confidence interval lower and upper uncertainty bounds for agricultural GHG emissions at –11% and +18% (CH_4 emissions from enteric fermentation) and –18% and +20% and –16% and +24% (CH_4 and N_2O emissions from manure management, respectively; U.S. EPA 2018). Whereas emissions from enteric fermentation are relatively well studied and predictable, there is larger uncertainty regarding manure CH_4 emissions and net effects of different intensities and types of grazing (see also Ch. 10: Grasslands, p. 399). Large datasets have established CH_4 emissions from enteric fermentation at 16 to19 g per kg dry matter intake for dairy cows (higher-producing cows have lower emissions per unit of feed intake) to 21 to 22 g per kg dry matter intake for beef cows on pasture (Hristov et al., 2013b). Levels of manure CH_4 emissions, however, largely depend on the type of storage facility, duration of storage, and climate (Montes et al., 2013). Emissions from certain dairy manure systems (e.g., flush systems with settling ponds and anaerobic lagoons) can be higher than estimates used by current inventories. So-called top-down approaches have suggested that livestock CH_4 emissions are considerably greater than EPA inventories. Miller et al. (2013) and Wecht et al. (2014) proposed that livestock CH_4 emissions may be in the range of 12 to 17 Tg per year, which is roughly 30% and 85% greater than EPA's estimate for 2012 (U.S. EPA 2016). Thus, future research is needed to address these discrepancies and reconcile top-down and bottom-up estimates.

Large uncertainties in GHG emissions from agricultural systems also exist because of their high spatial and temporal variability, measurement methods, cropping systems, management practices, and variations of soil and climatic conditions among regions (Hristov et al., 2017b, 2018). Uncertainty in GHG measurements often exceeds 100% (Parkin and Venterea 2010). Finally, there is considerable uncertainty in soil carbon accumulation and emissions from soils under different conditions and management practices, all of which are complicated by uncertainties about the total amount of land area under different management practices (see Ch. 12: Soils for more information on soil carbon balance).

5.7.2 Modeling and Modeling Uncertainties

Whole-farm models representing all major farm components and processes provide useful tools for integrating emission sources to predict farm-scale GHG emissions (Del Prado et al., 2013). By predicting emission processes and their interactions, models can provide a better understanding of production system emissions and be used to explore how different management decisions could affect GHG emissions. This approach has been used to estimate the carbon footprint of common U.S. dairy production systems at around 1 ± 0.1 kg CO_2e per kg fat- and protein-corrected milk produced, in which about half of these emissions come from enteric CH_4 emissions (Rotz and Thoma 2017). With a similar approach, the carbon footprint of beef cattle production was found to be 18.3 ± 1.7 kg CO_2e per kg carcass weight, with about 60% of emissions in the form of enteric and manure management CH_4 (Rotz et al., 2015).

Uncertainty exists in any measurement or projection of GHG emissions. The uncertainty of farm-scale projections is related to the uncertainty in projecting emissions from individual sources (Chianese et al., 2009). The IPCC (2006) suggested a ±20% uncertainty in predicting both enteric and manure management CH_4 emissions. Through the use of process-based models representing common management strategies for the United States, the uncertainty for predicting enteric emissions may be reduced to ±10%, but uncertainty for manure management likely will remain around ±20% (Chianese et al., 2009). Considering these uncertainties along with those of other agricultural emission sources, total GHG emissions can be determined with an uncertainty of ±10% to ±15%. As process-level models improve, verified with accurate measurements, this uncertainty can be reduced. As with inventories, uncertainties also are great for modeling agricultural carbon fluxes related to soil processes. Improving the modeling of these processes and incorporating them into large-scale carbon flux models will help increase understanding and reduce uncertainties in carbon models for agricultural lands.

SUPPORTING EVIDENCE

KEY FINDING 1

Agricultural greenhouse gas (GHG) emissions in 2015 totaled 567 teragrams (Tg) of carbon dioxide equivalent (CO_2e) in the United States and 60 Tg CO_2e in Canada, not including land-use change; for Mexico, total agricultural GHG emissions were 80 Tg CO_2e in 2014 (not including land-use change) (*high confidence*). The major agricultural non-CO_2 emission sources were nitrous oxide (N_2O) from cropped and grazed soils and enteric methane (CH_4) from livestock (*very high confidence, very likely*).

Description of evidence base

Bottom-up estimates of GHG emissions are from U.S. EPA (2018), ECCC (2017), and FAOSTAT (2017) data for the United States, Canada, and Mexico, respectively. These estimates include rice cultivation, field burning of agricultural residues, fertilization and liming, enteric fermentation, and manure management, but they do not include land-use change. The major components of agricultural non-CO_2 emissions have been consistent in numerous reports including those listed above for the emissions estimates part of this Key Finding.

Major uncertainties

Uncertainty exists in any measurement or projection of GHG emissions. Emissions from enteric fermentation are relatively well studied and predictable, but there is larger uncertainty regarding manure CH_4 and N_2O emissions. Considerable uncertainty exists in soil carbon accumulation and quantities as well as in terms of emissions from soils under different conditions and management practices. There are large uncertainties in GHG emissions from agricultural cropping systems due to high spatial and temporal variability, measurement methods, cropping systems, management practices, and variations in soil and climatic conditions among regions.

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

There is very high certainty that N_2O and CH_4 are the major agricultural non-CO_2 emission sources. There is high confidence in the numerical estimates.

Summary sentence or paragraph that integrates the above information

For Key Finding 1, enteric CH_4 emissions are predictable, but GHG emissions from manure applications or management and agricultural soil and cropping systems are less certain.

KEY FINDING 2

Agricultural regional carbon budgets and net emissions are directly affected by human decision making. Trends in food production and agricultural management, and thus carbon budgets, can fluctuate significantly with changes in global markets, diets, consumer demand, regional policies, and incentives (*very high confidence*).

Description of evidence base

Key Finding 2 and the supporting text document the changes resulting from shifts in policy as summarized by Nelson et al. (2009).

Major uncertainties

Major uncertainties related to this Key Finding are the extent and direction of direct and indirect changes in emissions. A change in agricultural management, prompted by many possible social, economic, and policy drivers, often affects both onsite emissions (e.g., soil carbon, N_2O, and CH_4 emissions) and offsite emissions occurring upstream and downstream (e.g., in energy used for inputs to production and indirect land-use change; Nelson et al., 2009).

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

The confidence that agricultural regional carbon budgets and net emissions are directly affected by human decision making is very high.

Summary sentence or paragraph that integrates the above information

For Key Finding 2, human decisions and policy very likely will affect food production and agricultural management. Management choices strongly influence emissions and soil carbon stocks.

KEY FINDING 3

Most cropland carbon stocks are in the soil, and cropland management practices can increase or decrease soil carbon stocks. Integration of practices that can increase soil carbon stocks include maintaining land cover with vegetation (especially deep-rooted perennials and cover crops), protecting the soil from erosion (using reduced or no tillage), and improving nutrient management. The magnitude and longevity of management-related carbon stock changes have strong environmental and regional differences, and they are subject to subsequent changes in management practices (*high confidence, likely*).

Description of evidence base

Most of this carbon pool exists within soils, with less than 5% residing in cropland vegetation, a finding consistent with previous reports such as the *First State of the Carbon Cycle Report* (CCSP 2007) and USDA (2016). The U.S. Department of Agriculture's Natural Resources Conservation Service has established 15 standard soil health conservation practices, which have the potential to increase soil carbon and coincidently reduce atmospheric CO_2 (Chambers et al., 2016). Evidence indicates that adoption of no tillage may increase carbon storage, especially in the soil surface, compared to conventional tillage (Chambers et al., 2016; Paustian et al., 2016; Sperow 2016), although soil heterogeneity and slow rates of change make the conclusive measurement of short-term changes difficult. It may not be appropriate to assume that adopting no tillage will sequester carbon over the long term or mitigate GHG emissions (e.g., Baker et al., 2007; Luo et al., 2010; Powlson et al., 2014; Ugarte et al., 2014). Practices that convert lands from perennial systems, such as converting retired lands or other lands to row crops, will release stored carbon back to the atmosphere (Gelfand et al., 2011; Huang et al., 2002). Conversely, management practices with the potential to release stored carbon are the inadequate return of crop residues (Blanco-Canqui and Lal 2009) and aggressive tillage (Conant et al., 2007). Conservation practices improve soil aeration, aggregate stability, and nutrient reserves, while modulating temperature and water and increasing microbial activity and diversity. As a result, soil is more resilient to climate variability and more productive (Lal 2015; Lehman et al., 2015).

Major uncertainties

Major uncertainties are related to individual practices such as no-tillage management, in particular the magnitude and longevity of changes to soil carbon stocks. Meta-analyses by Luo et al. (2010) and Ugarte et al. (2014) suggest that other factors contributing to variability in soil organic carbon sequestration include climatic and soil properties interacting with management factors (e.g., cropping frequency, crop rotation diversity, nitrogen, and drainage), along with impacts on rooting depth and above- and belowground biomass. Future shifts in management can reverse gains.

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

Confidence that conservation practices have the potential to increase soil carbon stocks is high.

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

Implementation of conservation practices on croplands is likely to increase soil carbon stocks. Adopting conservation practices also provides co-benefits such as erosion control.

Summary sentence or paragraph that integrates the above information

For Key Finding 3, implementing conservation practices has strong undisputed co-benefits, including reducing erosion, and may increase soil carbon stocks over time, provided that the practices are continued. Cessation of conservation with reversion to degrading practices will result in a loss of carbon stocks and reduction of co-benefits.

KEY FINDING 4

North America's growing population can achieve benefits such as reduced GHG emissions, lowered net global warming potential, increased water and air quality, reduced CH_4 flux in flooded or relatively anoxic systems, and increased food availability by optimizing nitrogen fertilizer management to sustain crop yields and reduce nitrogen losses to air and water (*high confidence, likely*).

Description of evidence base

Agricultural soil management (i.e., synthetic nitrogen fertilizer) is a major source of GHG fluxes in North America (FAOSTAT 2017). Matching nitrogen fertilizer needs to crop needs reduces the risk of loss to air and water (Robertson and Grace 2004; Wang et al., 2011). Nitrogen fertilizer additions generally lead to increased CH_4 emissions and decreased CH_4 oxidation from soils, particularly under anoxic conditions or flooded soil systems such as rice (Liu and Greaver 2009).

Major uncertainties

Large uncertainties in GHG emissions from agricultural systems exist due to high spatial and temporal variability, measurement methods, cropping systems, management practices, and variations in soil and climatic conditions among regions (Parkin and Venterea 2010).

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

There is high confidence that matching crop needs to nitrogen fertilizer applications can reduce fertilizer-induced GHG emissions.

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

Avoiding excessive nitrogen fertilizer applications likely will reduce GHG emissions and provide co-benefits such as air and water quality protections.

Summary sentence or paragraph that integrates the above information

For Key Finding 4, nitrogen fertilizer is needed to support grain production. In general, there is high confidence that improving nitrogen management to avoid excess applications can reduce GHG emissions and provide co-benefits. However, considerable uncertainty still exists regarding absolute GHG fluxes.

KEY FINDING 5

Various strategies are available to mitigate livestock enteric and manure CH_4 emissions. Promising and readily applicable technologies can reduce enteric CH_4 emissions from ruminants by 20% to 30%. Other mitigation technologies can reduce manure CH_4 emissions by 30% to 50%, on average, and in some cases as much as 80%. Methane mitigation strategies have to be evaluated on a production-system scale to account for emission tradeoffs and co-benefits such as improved feed efficiency or productivity in livestock (*high confidence, likely*).

Description of evidence base

Non-CO_2 GHG mitigation strategies for livestock have been summarized in several comprehensive reviews (Montes et al., 2013; Hristov et al., 2013b; Herrero et al., 2016).

Major uncertainties

Uncertainty exists in any measurement or projection of GHG emissions. Uncertainties of GHG mitigation options are related to 1) uncertainties in projecting emissions, 2) uncertainties in projecting mitigation potential, and 3) uncertainties in the extent of the adoption of mitigation options. The uncertainty of farm-scale projections is related to the uncertainty in projecting emissions from individual sources (Chianese et al., 2009). The IPCC (2006) suggested a ±20% uncertainty in projecting both enteric and manure management CH_4 emissions. Through the use of process-based models representing common management strategies for the United States, the uncertainty for projecting enteric emissions may be reduced to ±10%, but uncertainty for manure management likely remains around ±20% (Chianese et al., 2009). Considering these uncertainties along with those of other agricultural emission sources, total GHG emissions can be determined with an uncertainty of ±10% to ±15%. As process-level models improve, verified with accurate measurements, this uncertainty can be reduced.

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

There is high confidence that mitigation technologies can reduce livestock enteric and manure emissions. These technologies include practices related to reducing emissions from enteric fermentation (i.e., cattle) and manure management (i.e., cattle and swine) as discussed by Hristov et al. (2013b) and Herrero et al. (2016). Other potential CH_4 mitigation strategies include manure solids separation, aeration, acidification, biofiltration, composting, and anaerobic digestion (Montes et al., 2013).

Summary sentence or paragraph that integrates the above information

For Key Finding 5, effective enteric fermentation and manure emissions mitigation options are available or are expected to be available in the near future. Impact will depend on cost-effectiveness and adoption rate.

KEY FINDING 6

Projected climate change likely will increase CH_4 emissions from livestock manure management locations, but it will have a lesser impact on enteric CH_4 emissions (*high confidence*). Potential effects of climate change on agricultural soil carbon stocks are difficult to assess because they will vary according to the nature of the change, onsite ecosystem characteristics, production system, and management type (*high confidence*).

Description of evidence base

A recent analysis for the northeastern United States (Hristov et al., 2017a) estimated potential climate change effects on livestock GHG emissions.

Major uncertainties

Uncertainties include projecting climate change, its effect on animal feed intake (which determines enteric CH_4 emissions), animals' ability to adapt to climate change, and uncertainties regarding trends in animal productivity. The effect of increased temperature on manure GHG emissions is more predictable.

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

There is high confidence that projected temperature increases are expected to decrease dry matter intake by dairy cows due to heat stress (Hristov et al., 2017a), while CH_4 emissions from manure decomposition are expected to increase (Rotz et al., 2016). Climate change effects on soil carbon sequestration balances and interactions with temperature are difficult to predict because temperature may regionally improve or degrade growing conditions, thereby shifting associated biomass inputs (Zhao et al., 2017; Tubiello et al., 2007). Likewise, increased atmospheric CO_2 will increase soil CO_2 respiration and mineralization as much as carbon inputs, resulting in little net change in soil carbon pools (Dieleman et al., 2012; Todd-Brown et al., 2014; van Groenigen et al., 2014).

Summary sentence or paragraph that integrates the above information

For Key Finding 6, projected climate changes likely will not significantly affect enteric CH_4 emissions from livestock, but increased temperature is expected to increase manure GHG emissions.

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6 Social Science Perspectives on Carbon

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KEY FINDINGS

1. *Broadened Approaches*—A range of social scientific research approaches, including people-centered analyses of energy use, governance, vulnerability, scenarios, social-ecological systems, sociotechnical transitions, social networks, and social practices, complements physical science research and informs decision making. Approaches that are people centered and multidisciplinary emphasize that carbon-relevant decisions are often not about energy, transportation, infrastructure, or agriculture, as such, but rather about style, daily living, comfort, convenience, health, and other priorities (*very high confidence*).
2. *Assumed versus Actual Choices*—Planners have assumed economically rational energy-use and consumption behaviors and thus have failed to predict actual choices, behaviors, and intervening developments, leading to large gaps between predicted rates of economically attractive purchases of technologies with lower carbon footprints and actual realized purchase rates (*high confidence*).
3. *Social Nature of Energy Use*—Opportunities to go beyond a narrow focus on the energy-efficiency industry to recognize and account for the social nature of energy use include 1) engaging in market transformation activities aimed at upstream actors and organizations in supply chains, 2) implementing efficiency codes and standards for buildings and technologies, 3) conducting research to understand how people's behaviors socially vary and place different loads on even the most efficient energy-using equipment, and 4) adding consideration of what people actually do with energy-using equipment to plans for technology and efficiency improvements (*high confidence*).
4. *Governance Systems*—Research that examines governance at multiple formal levels (international, national, state/province, cities, other communities) as well as informal processes will identify overlaps and gaps and deepen understanding of effective processes and opportunities involved in carbon management, including a focus on benefits such as health, traffic management, agricultural sustainability, and reduced inequality (*medium confidence*).

6.1 Introduction: The Social Embeddedness of Carbon

The goal of this chapter is to provide perspectives of social science research and analysis that go beyond much of available carbon science work that is sector based and economically minded—research that as yet is not sufficiently reflected in carbon cycle studies. The research discussed in this chapter thus is not intended to be a comprehensive, integrated picture of the society-carbon interaction that produces carbon emissions. Rather, the framing of the research discussed here begins with people and their social structures. This framing is different from, but complementary to, that used in the research discussed in most other chapters in the *Second State of the Carbon Cycle Report* (SOCCR2; see Box 6.1, Two Framings of Research Relevant to the Carbon Cycle, p. 266).

The framing in most of SOCCR2 begins with a description of the carbon cycle in spatial and quantitative terms, proceeds to calculations of carbon emissions to the atmosphere and their sectoral sources, and then analyzes human activities that contribute to the carbon emissions in those sectors and the impacts that increasing emissions have on physical and social systems. This framing has been used in physical science research and extended to much energy and economics research, areas not covered in this chapter.

Knowledge gained through this research framing can identify opportunities for carbon management that target the largest emissions categories (e.g., fossil fuel–based energy and transportation, urban settings, and agriculture; see Ch. 3: Energy Systems, p. 110; Ch. 4: Understanding Urban Carbon Fluxes, p. 189; and Ch. 5: Agriculture, p. 229). However,

Box 6.1 Two Framings of Research Relevant to the Carbon Cycle

Framing starting with the carbon cycle (CC):

Global CC / Fluxes → Regional CC / Fluxes → Emissions by Sector → Social "Drivers"

Framing starting with people (this chapter):

Social Structures / Processes (SS/P) → Carbon Content of SS/P → Feasible Changes

barriers to such technically oriented opportunities exist in ways of life and social or governance structures at local to global levels.

This chapter, in contrast, discusses research conducted using a framing that begins with an analysis of social conditions and structures in which carbon plays various roles. In this alternative framing, 1) the myriad and interrelated ways carbon-embedded structures and processes support ways of life become evident and 2) the socially feasible pathways to opportunities for carbon management emerge in the larger societal context. Pathways indicated under research using a people-centered framing are likely to solve multiple social goals rather than trying to achieve the single goal of emissions reductions because institutions and groups (e.g., governments, businesses, and families) have a different and broader set of issues to deal with than carbon management. Similarly, decisions that affect carbon emissions will be based on multiple factors—often including economic costs but also family, time, job, convenience, what others do, what is best for the group or organization, and other considerations.

6.1.1 Carbon Embeddedness in Social Structures and Processes

Although carbon is part of (i.e., embedded in; see Box 6.2, Embedded Carbon, this page) most social structures and processes, it is largely invisible to people as they go about their daily lives. People may (or may not) think of carbon as they see smokestacks or burn wood in a campfire because the carbon-emitting processes that produce electricity, heat buildings, and drive industrial processes may stay in the background, out of sight and out of mind.

Box 6.2 Embedded Carbon

Social science perspectives describe social arrangements and practices and then identify how carbon is embedded in them. "Embeddedness" means that carbon is an integral but often invisible part of how people lead their lives, so they do not think of themselves as using carbon but instead see the services and products without seeing their embedded carbon. Moreover, people do not often make choices about carbon as such—they choose from what is available in the market.

Nevertheless, emissions and associated structures and processes start with people—their needs and wants and how various social, political, and economic configurations and technologies both shape and are shaped by those needs and wants. From energy choices and services to economic policies and from urban hardscapes to rural landscapes, carbon is emitted, conserved, or captured as people work, travel, eat, and engage in other everyday activities and as human institutions and economic systems form and operate (see Figure 6.1, p. 267).

Research that begins by examining social structures and practices analyzes categories that may include standard sectors such as energy, transportation, buildings, and agriculture, but starting with people brings in a wide range of other topics as well. Eating, for example, a seemingly straightforward activity, encompasses a vast system of farm and

Figure 6.1. Carbon Embeddedness. As people work, learn, run errands, travel, and enjoy family and civic life, carbon is a common "thread," running through their infrastructure, tools, and environment (represented here by the white "threads" in the figure). Thus, analysis of the carbon cycle will be enhanced by identifying human uses of and reliance on carbon.

food production, agricultural policies and supports, imports and exports, transportation, middleman transactions, retail stores (e.g., location and products offered), and people's preferences along with income and health considerations. Obtaining and keeping a job, considered in a people-centered systems approach, similarly involves a range of activities such as educational opportunities and costs; income levels; locational factors such as housing, transportation, and commercial buildings (and/or home offices); access to electronic technologies; and health insurance and other benefits—the list could go on.

Social science research that examines people and the social embeddedness of carbon includes different approaches based on the research questions to be answered but often emphasizes systems and network perspectives and multiple societal factors within those systems. Because these approaches represent lines of research not assessed in the *First State of the Carbon Cycle Report* (SOCCR1; CCSP 2007), some references may predate that document.

6.1.2 Chapter Structure

First, this chapter discusses five approaches that represent lines of social science research within the climate change community, lines that are well established but usually not framed as questions about societal relationships with carbon or the carbon cycle.

- Section 6.2, p. 268. At individual, institutional, and organizational levels, behavioral research explores connections among motivation,

intention, and actors with regard to energy-related consumption and other individual and social behaviors.

- Section 6.3, p. 274. Governance research provides insights into why and how policy-environment decisions are made and implemented through both informal and formal processes.
- Section 6.4, p. 276. Scenarios of the future point to the power of connecting climate change and carbon emissions to their social-economic (socioeconomic) consequences.
- Section 6.5, p. 278. Vulnerability assessments specify who will probably be harmed by climate change, what the harm will be, and where interventions can be made at regional and local levels.
- Section 6.6, p. 279. A socioecological systems perspective demonstrates linkages among climate change–related hazards and social vulnerabilities and risks.

Next, the chapter introduces three less well known social-scientific approaches that hold potential for increasing basic understanding and providing useful future directions for decision makers to consider.

- Section 6.7, p. 280. Sociotechnical transition studies illuminate how technological transitions happen as actors, artifacts, and processes shape and reshape each other.
- Section 6.8, p. 282. Social network analyses map the connections among people with similar interests and goals, thus showing potentially changeable pathways and roadblocks.
- Section 6.9, p. 282. Social practice analyses reveal the configurations that produce emissions but also support valued, or locked-in, ways of life.

The final three sections are crosscutting. Section 6.10, p. 284, points out the crucial roles that communication and stakeholder involvement play in people-centered research. Section 6.11, pp. 285, discusses opportunities to reduce carbon emissions, including individual and social actions at various levels and timescales. Finally, Section 6.12, p. 287, provides a brief summary of findings, as well as specific steps in the path for research related to social systems and embedded carbon.

Essential to research in all these areas is increased interaction between researchers and stakeholders. Economic theory may posit people as self-interested individuals who assess a full set of information before making decisions that maximize utility at the lowest cost, but actual decision makers consider others' opinions and approval, weigh other characteristics more highly than cost, and satisfice rather than maximize (i.e., they settle for the first minimally acceptable option rather than weighing all options using multiple criteria). Understanding how people really decide and change requires questioning, observing, and interacting. According to Ch. 18: Carbon Cycle Science in Support of Decision Making, p. 728, researchers and stakeholders must co-produce knowledge.

6.2 Energy Behavior and Embedded Carbon

Although social scientists have investigated the social processes responsible for growth in carbon emissions and decline in the capacity of carbon sinks, enlarging and enriching this knowledgebase would provide better guidance for policy that addresses systems, technology design, and other efforts to reduce overall carbon emissions. In addition to energy production, expansive urban settlements, and transport systems and activities (see Ch. 3: Energy Systems, p. 110, and Ch. 4: Understanding Urban Carbon Fluxes, p. 189), researchers have considered the acquisition and accumulation of goods, as well as their embodied energy and carbon contents. Demand-side research has focused on the technical characteristics and uses of energy-powered devices, in addition to the patterns of energy demand and carbon emissions resulting from the use of buildings and appliances (Sovacool 2014). Economics work aside, the bulk of social

and behavioral sciences research and attention with respect to energy demand has been concerned with encouraging energy conservation and emissions reductions predominantly by individuals and households (Dietz et al., 2009; Stern et al., 2016; i.e., generally, behavior at the level of devices). There has been less attention to the structure and evolution of energy demand and its carbon emissions implications. For example, research on people's role in residential air conditioning has focused on how people use their air conditioning systems and how to get people to use less, rather than on the social processes involved in housing construction, device design, and lifestyles that encourage increased installation of air conditioning in buildings and vehicles.

6.2.1 What Does the Research Show?

In contrast to relating energy use and carbon emissions to devices, social science researchers have emphasized that energy use and carbon emissions are deeply interwoven—"embedded"—features of social life. Energy consumption and emissions are part of people's routines and habits, within patterns of social interaction, and are governed largely by social norms and expectations, without regard for or reference to energy sources or carbon emissions resulting from these activities. Moreover, in North America, although energy infrastructure (e.g., power lines and electrical cords) is visible, energy itself is virtually invisible to people except in special cases (e.g., cooking with a gas flame) or under unusual circumstances (e.g., appliance or system failures, grid blackouts, or energy-supply crises; Nye 2013; Rupp 2016; Shove 1997; Trentmann 2009). Although modern North American lifestyles are constrained somewhat by available energy sources and costs, they have come to represent a set of living standards and desires—normal expectations that exert growing "demands" for easily accessible energy that currently almost always is supplied across long distances and often requires considerable, yet invisible to the user, carbon emissions. Increasing installations of solar microgeneration, discussed below, could shift users' relationships with energy systems to some extent, making the sources and limitations of energy supply clearer. However, if users are to contribute to major reductions in carbon emissions, they also will modify their living standards and daily activities in the name of what they now may see as intangible environmental benefits. Thus, even if emissions were visible and easily accountable, major change would not necessarily occur, unless people see that the benefits will improve their lives in measurable ways.

As noted, both the nature of energy-using behaviors and their susceptibility to change (mostly through formal interventions) have been investigated in studies by researchers and analysts in the energy-efficiency field as well as by social scientists working in other realms. Economics has provided the most generalizable theories of investment decisions and of change (i.e., reduced consumption in response to increased unit price of energy), but the strength of relationships is often quite low (Bernstein and Griffin 2006; Kriström 2008; Lijesen 2007), related to aggregate rather than individual patterns, and compromised by what economics literature identifies as market and nonmarket failures (Jaffe and Stavins 1994).

The other, less-explicit economic explanations for energy-use behaviors and susceptibility to change given so far tend to be general and cannot be readily applied as mechanisms for reducing rates of carbon emissions, ranging from the abstract and macrohistorical (e.g., aggregate conditions and factors such as "affluence," "consumer preferences," and "institutional barriers"; NRC 2010) to the micropsychological (e.g., "motivations," "intentions," "values," "beliefs," and "propensities to adopt"; Shove 2010). These explanations often come with the assumption that actions are driven by these micropsychological properties (Ignelzi et al., 2013; Sussman et al., 2016). The descriptive layers do present ways of "seeing" people as diverse and evolving participants in energy use. Unclear, however, are how and how much the underlying qualities described in these analyses might be deliberately changed and, if they were, whether the desired reductions of energy use and carbon emissions might be achieved.

Leading-edge research has focused on diversity across individuals and households and on the layered structure of this diversity as opposed to simpler explanations rooted in isolated choices, with a particular emphasis in recent literature on populations, practices, patterns, and behavioral economics.

- Observed energy-use levels vary dramatically across populations (e.g., households or firms) due to differences in activity patterns, technical efficiency, and environmental conditions. Energy-using activity patterns are shared within groups, and different groups may have widely varying patterns of activity and modes (Lutzenhiser et al., 2017; Sonderegger 1978).
- Activities and practices, many involving energy-using equipment, emerge and are elaborated over time; some decline while others persist (Shove et al., 2012) as people modify and adapt physical systems to better meet social and cultural purposes and, in turn, modify what they do as they are "recruited" by and adopt practices (Shove et al., 2012).
- Patterns are stabilized and constrained by the characteristics of their energized technologies and infrastructure, much more so than being clusters of discrete personal behavioral choices (e.g., Shove et al., 2012).
- Insights from behavioral economics may be useful in designing instruments for energy-related behavioral change (Allcott and Mullainathan 2010) by focusing on the microstructure of decisions.

However, the complex and nuanced dynamics of energy use are not reported with much clarity in the literature. Future research could focus on understanding what influences the self-organizing nature of daily activity rather than directly engaging individuals and their behaviors.

Reviews find no overarching theory or set of consensus research methods (Lutzenhiser 1993; Wilson and Dowlatabadi 2007) and no cumulative practical understanding of "what works." Instead, there are compartmentalized disciplinary knowledgebases guided by divergent perspectives and distinct methodological preferences. In the area of applied research, narrow perspectives of program- and policy-centered research have focused on the efficacy of specific interventions or instruments, finding that certain actions may be more amenable to intervention-based change within some groups (Abrahamse et al., 2005; Ehrhardt-Martinez and Laitner 2010). Applied research on energy-conservation actions, such as equipment purchase decisions, has long been dominated by short-term policy objectives (such as responding to demand or meeting utility-savings goals) even as these goals are increasingly translated to the longer timelines of supply planning and climate change. Energy use is represented typically as averages and norms, making calculations and planning appear more tractable but generally hiding the dynamic sources, forms, and logics that create energy use.

Programs and projects that focus on or pay attention to "behavioral energy-savings potential" usually are not connected to relevant insights and framings from the social sciences or accompanied by serious considerations of how this potential might be achieved. (For a history and critique, see Wilhite et al., 2000.) These programs typically focus on discrete actions relative to assumed normative behavior—parallel to notions of technical potential via efficiency—rather than attending to how behaviors are organized (e.g., as addressed by social practice theory; see Section 6.9, p. 282). Thus, they miss opportunities provided by recognizing how systems, rather than individuals, create energy use. The findings of behavioral analysts have been used in experiments and case studies on behavioral economics (Ariely 2010; Alcott and Mullainathan 2010; Alcott and Rogers 2014), concept of "influence" (Cialdini 2010), social marketing (McKenzie-Mohr and Smith 2007), primary motivations (Pink 2010), and "nudges" (Thaler and Sunstein 2009). But that use has been without broad influence on programs and projects (Frederiks et al., 2015). Interestingly, behavioral economics experiments have found that economic incentives

and awards are weak motivators compared to, for instance, friendship ties (Ariely 2010).

Given the calls for absolute reductions in greenhouse gas (GHG) emissions rather than relative savings from energy efficiency, there is a need for a broader multidisciplinary social scientific and applied view (Keirstead 2006; Lutzenhiser et al., 2017). However, efforts to identify theoretically grounded and evidence-based "design principles" for carbon-reduction interventions are just beginning (Stern et al., 2016). Three factors hamper such efforts: 1) the absence of a systematic social science carbon-reduction research agenda, 2) the lack of adequate support from science and environmental policy agencies for social science contributions as a core component of energy-transition and carbon-mitigation research, and 3) insufficient experience in drawing together disparate scientific perspectives to address such complex high-level problems. Programs that are beginning to integrate scientific perspectives include those discussed throughout this chapter; findings from such programs are reiterated in Section 6.11, p. 285.

6.2.2 Learning from the Energy-Efficiency Experience

A good deal of the research on energy use to date has been the result of U.S. federal, state, and local policy initiatives to encourage energy efficiency (Lutzenhiser and Shove 1999). Those initiatives have recognized since the 1970s that "energy services" such as cooking, washing, heating, and cooling could be provided via technologies that, technically at least, consume much smaller amounts of energy than then-current models (e.g., Gillingham et al., 2006). Thus, public policy has focused on increasing the efficiency of appliances and buildings to displace a fraction of current consumption and delay the need for new sources of energy. Emissions reduction can be a co-benefit of energy-efficiency improvement. However, differences between efficiency improvements and reductions in absolute emissions over time are easily overlooked.

Also, because interventions to improve the energy efficiency of technologies have been funded largely by utility ratepayers under the scrutiny of public regulators, the primary focus has been on hardware upgrades and "cost-effectiveness"—not on energy users or their habits, desires, or social practices. The kinds of research needed to support these efforts have been engineering studies and economic cost-benefit analyses. Emphasis has been placed on energy cost savings.

However, behavioral science research related to interventions has shown that energy demand is not particularly price sensitive (Kriström 2008). This research has pointed to the importance of environmental values, social influences, and concerns for others as more frequent and actionable motivations for carbon-reducing equipment purchases and energy-use behaviors (Abrahamse et al., 2005; Stern et al., 2016).

Large "efficiency gaps"—gaps between predicted rates of economically attractive purchases of more efficient technology and actual realized adoption rates—have been reported regularly (Allcott and Greenstone 2012; Gillingham and Palmer 2014; Jaffee and Stavins 1994; Shove 1998). In short, energy appears to be an area where markets do not function as predicted by rational economic behavior as envisioned by classical economics—or these definitions are too simple, and there are inadequate data and understanding to represent sufficiently the complex decision processes. Programmatic explanations point to "barriers" to efficiency program participation (Golove and Eto 1996). Lists of barriers (e.g., "high discount rates" or "risk aversion") often are labels or glosses that say more about policy perspectives and program priorities than the nonadoption behaviors of actual energy users or their relationships to the energy uses targeted for change (Blumstein et al., 1980). Also, recurrent questions have been raised about "rebound effects"—the case in which expected savings from technology adoption may not be realized because of choices, behaviors, and intervening developments not predicted by efficiency-intervention planners (Gillingham et al., 2016; Herring 1999). In addition, traditional definitions of energy efficiency are

not necessarily closely aligned with issues related to carbon emissions because not only do they not take into account the carbon content of supply, they focus on relative savings rather than absolute emissions (Moezzi and Diamond 2005). More recently, scholars have stressed the importance of the "macrorebound" of carbon and energy in a growth economy (Wilhite 2016).

Many of the problems with adoption of efficient technologies can be traced to the existing situation. Regulatory logics and institutional constraints push the energy-efficiency industry, itself a socially structured enterprise, to assume that choices made by energy users are well informed and economically rational (Lutzenhiser 2014). This assumption has encouraged efforts to improve the quantity and quality of information available to energy users, with an emphasis on communicating the economic benefits of energy savings. But psychological research has shown that the "delivery" of information is far from a simple matter and that even the highest-quality information supplied as directly as possible, whether via old media or new, frequently is not acted on in the way that program developers imagine that it should, or would, be (Owens and Driffill 2008; see Section 6.10, p. 284). Even well-informed social actors routinely pass over clear and simple "rational" choices that would save money by saving energy.

This disconnect between assumptions and outcomes is as true for large firms and governmental agencies that have sophisticated information systems, analytic capacities, and strong economic interests (Biggart and Lutzenhiser 2007) as it is for individuals, households, and other groups. Explanations point to organizational structure, competing priorities and internal conflicts, risk and trust issues, and weak regulation (Stern et al., 2016). However, there also are instances of organizations leading the way in carbon reduction through corporate investment in renewable energy sources, supply-chain efficiency improvements, and energy-conscious acquisition and operation of buildings and other capital equipment (Prindle 2010; Stern et al., 2016). Research to determine how organizations variously relate to and manage carbon emissions, often in ways that defy simple explanation (e.g., by reference to cost and benefits, regulatory influence, or competition) is in its initial stages.

6.2.3 Expanding the Efficiency Policy Framework: Insights about Energy and Social Systems

Evidence suggests that various energy-efficiency technology innovations and policy initiatives undertaken over 40 years of activity in this field have saved energy (e.g., NRC 2001). However, the narrow regulatory focus and underperformance of these innovations and initiatives relative to idealized models, as discussed above, reinforce the importance of moving beyond a traditionally narrow energy-efficiency industry focus on producing energy reductions at less cost than supply (Lutzenhiser 2014). Future research and institutional changes need to recognize the social nature of energy use—including the social organization of technologies and energy systems, the social patterning of energy demands, the social nature of energy-conservation choices, and the social delivery of energy-efficiency programs and policies.

Although these social issues have rarely been explicitly considered in energy-efficiency policy or associated research, the "market transformation" strand of efficiency intervention is an important exception and success story. These activities are aimed at "upstream" actors and organizations in supply chains that engage with technology designers, manufacturers, wholesalers, and retailers to encourage, facilitate, and provide financial incentives for bringing more efficient technologies to the marketplace at appealing prices (Blumstein et al., 2000). Also, efforts by some states and the U.S. federal government to regulate the energy-using characteristics of appliances and buildings through codes and standards have had wider systemic impacts on technology efficiency. These upstream changes to improve efficiency have occurred despite strong political opposition from an array of groups and interests holding stakes in existing technologies, infrastructures, and supply arrangements (Sovacool 2008). Considerable social science research is needed on carbon management

and the market systems, supply chains, and organizational networks involved in shaping and delivering technologies (Janda and Parag 2013).

Several other strands of social research on energy use and conservation also hold promise. One has focused on the considerable variation in energy use across populations and among subgroups of energy users. Utilities and other efficiency industry actors have sometimes identified "segments" of energy users to target marketing and communications to their interests. But these efforts, redefined as the lifestyle dimension of energy—how people's behaviors socially vary and place different loads on even the most efficient energy-using equipment—offer opportunities for a better understanding of the invisible and embedded dimensions of social carbon management. In addition, periodic energy-supply crises, such as the 2001 to 2002 California electricity shortages and the 2008 loss of a substantial fraction of electricity supply to Juneau, Alaska, have provided "natural experiments" that highlight variations in energy use and in people's willingness or ability to conserve. Also shown is the malleability of taken-for-granted practices when supply is suddenly called into question (Lutzenhiser et al., 2004; Pasquier 2011) or general economic conditions worsen such as in the 2007 to 2009 recession (see Ch. 2: The North American Carbon Budget, p. 71). In addition, the past decade has seen a growing appreciation of "behavioral potentials" for energy savings (e.g., in equipment-use patterns and practices). Utility regulators and efficiency advocates have responded by adding the modification of what people actually do with energy-using equipment to the technology-efficiency improvements in their agenda.

Different strategies have been proposed to encourage those changes. A primary focus has been on mass delivery of energy usage–related information enabled by advances in electronic metering and data warehousing. The results indicate some modest aggregate reductions in overall electricity demands (Karlin et al., 2015; Power System Engineering 2010; Todd et al., 2014), even in a number of states where utility regulators only mandated delivery of information to allow persons to compare their usage to that of others (Allcott 2011; Allcott and Rogers 2014). However, these efforts have been limited in depth and aims—at least, when measured against goals—and represent small investments compared to technology-focused efficiency activities.

Despite an explicit linking of behavior changes to climate change by some academic and public-sector actors (e.g., within the Behavior Energy and Climate Change Conference, held annually since 2007 (ACEEE/BECC 2016)), the social sources and logics of energy-using practices, habits, lifestyles, and behaviors, as well as their organization and how they change continue to receive little systematic attention in U.S. scholarship. There is progress, for example, in the biannual European Summer Study on Energy Efficiency and in other efforts to "push the envelope" of energy-efficiency thinking and intervention by augmenting the classic economics framework (Frederiks et al., 2015), but this work tends to be siloed. However, there is valuable experience that can be gained from careful attention to successes and failures of energy-efficiency policy interventions, and that experience can serve as a starting point for broader and more universal carbon-reduction initiatives in the future.

6.2.4 Energy and Carbon Emissions Embedded in Complex Systems

Apart from efficiency, the other main route to reducing emissions from energy use has been developing and fostering lower-carbon energy sources. Human-centered research on this topic has focused on social acceptance of these alternatives. As much higher market shares of renewables start to become realized, researchers have started to pay closer attention to the intermittency and time-variability of renewable energy sources and how supply dynamics can synchronize with energy use rooted in temporal patterns of daily living. The social dimensions of technology acceptance (e.g., rooftop solar and wind farms, among newer technologies; nuclear power, among established technologies) and the social dynamics of routines and demand patterns (e.g., the locus of work and the cultural

definition of approved practices) will require concerted attention in social science research, carbon policy development, and energy system management. These efforts also must contend with the fact that the energetic structure of the modern North American society has developed with the experience and expectation of ready and virtually unlimited availability of energy at any time of day to fuel homes, cars, work, and play in any and all locations (see Ch. 4: Understanding Urban Carbon Fluxes, p. 189, for a discussion of urban forms).

The social-technical-environmental systems and systemic interactions involved in even the simplest energy-using and carbon-emitting human activities are complex and resistant to change via deliberate interventions—particularly on short time scales. And in that complexity, there is a "chicken and egg" quality to the relationships between supply (e.g., of goods, appliances, energy, buildings, vehicles, and transport options) and demand (i.e., for energy services). Demands are shaped and constrained by what is available, and effective supply requires that households and organizations actually consume what is offered. At the same time, suppliers attempt to encourage and increase demand through marketing, while consumers (certainly households but, most effectively, organizations) attempt to shape supply, such as through energy-related choices, regulations, and efficiency requirements. Capturing this complexity to show effective and democratic paths to reduced carbon emissions clearly requires more inclusive integrated models and increased understanding of the systems involved. This need for better models and understanding reflects earlier arguments (Douglas et al., 1998; Meadows 2008) and echoed in recent work on energy and climate change (Labanca and Bertoldi 2013; Shove et al., 2012). This also will require renewed attention to how evidence is evaluated. Next-generation analytic models and policy approaches will need to draw on new collaborations among research disciplines and between the scientific community and the social worlds in which energy is used and carbon is released to the atmosphere.

6.3 Governance and Carbon

A principal focus of climate change research comprises the kinds of governmental targets and timetables, policies, and regulations that will affect people's carbon-emitting and -capturing activities, such as energy production and land management. Social science research has expanded from an early focus on international and national governmental agreements and policies to a broader conception of carbon-relevant governance.

"Governance" refers to the processes and structures that steer society and the multiplicity of actors who are involved in this steering. The focus on governance, as opposed to governments, highlights the multiple channels through which collective interests are now pursued in the "post–strong state" era (Jordan et al., 2005; Kjaer 2004; Pierre and Peters 2000; Rhodes 1996). The complex configurations of processes and actors governing carbon emissions—who governs, with what authority, and through what means—set the context of the social, economic, and environmental costs and benefits provided by these systems (Marcotullio et al., 2014). To understand patterns of carbon emissions and, importantly, how to facilitate sustainable emissions trajectories, researchers and decision makers not only need to understand the governance processes guiding their production, maintenance, and conservation, but also need to identify feasible governance options for reducing carbon emissions.

6.3.1 Methods in Governance Research

Governance researchers use a range of quantitative and qualitative methods to understand both how particular governance arrangements arise and the social, economic, or policy consequences of different governance arrangements (Pierre and Peters 2000). Research also has focused on more normative approaches, including how governance arrangements can be designed to enhance participation and equity, be more democratic and accountable, improve efficiency, or support environmental objectives (Fainstein 2010; Hughes 2013; Pierre and Peters 2000; Sabatier et al., 2005). Increasingly, governance

research is using network-based approaches and theories to understand the complex web of actors and resources underpinning environmental planning and programs (Aylett 2013; Lubell et al., 2012; Paterson et al., 2013; Scholz and Wang 2006; see Section 6.8, p. 282, and Ch. 4: Understanding Urban Carbon Fluxes, p. 189, for a discussion of municipal networks). Governance research is often interdisciplinary, drawing on scholarship from political and policy sciences, economics, public administration, sociology, and geography (Kjaer 2004).

6.3.2 Key Findings from Governance Research

Despite previous calls for research (Canadell et al., 2010), few projects have explicitly examined the governance of the carbon cycle in North America, although there has been some work on carbon in a global context (e.g., Bumpus and Liverman 2008; Lövbrand and Stripple 2006). Rather, research tends to address carbon indirectly through analyses of governance processes and institutions operating at different scales and in different sectors related to climate change, sustainability, resilience, and even energy efficiency (Portney 2013; Wheeler 2008). Governance research increasingly has focused on the subnational level, where many North American states, provinces, and cities have taken the lead in setting ambitious GHG emissions–reduction targets and climate concerns are reshaping policy agendas across issue areas (Bulkeley and Betsill 2003, 2013; Hughes and Romero-Lankao 2014; Rabe 2004; Schreurs 2008; see Ch. 3: Energy Systems, p. 110, and Ch. 4: Understanding Urban Carbon Fluxes, p. 189, for examples of energy and urban governance). Carbon governance research also has a tendency to focus on particular sectors, such as agriculture, transportation, the built environment, and energy systems. (See Ch. 4 for a more detailed discussion of urban carbon governance.)

The work presented in other chapters indicates that energy use and production, urban areas, and agriculture are the key sectors shaping the North American carbon cycle. While scholarship typically engages with these sectors as distinctive governance realms, in reality they overlap and contradict one another in important ways. Urban form, policies, and lifestyles are responsible for more than two-thirds of global energy-related GHGs (IEA 2008), setting the demand for energy supplies and transportation behavior (see Ch. 3 and Ch. 4). Agricultural policies and priorities also shape the energy needs of this sector and, with the rise of biofuel production, can play an important role in facilitating or inhibiting renewable energy goals (Roberts and Schlenker 2013; see Ch. 5: Agriculture, p. 229). Governance research indicates that the governance systems for these three sectors differ from one another and, potentially over time, in three important ways—their sources of power and authority, institutional arrangements, and sets of their stakeholders engaged by governance processes.

Sources of power and authority can vary from more formal (e.g., U.S. federal regulations) to less formal (e.g., customer demand and preferences), and from more local (e.g., municipal governments) to more global (e.g., international agreements). Each sector engages a spectrum of power and authority sources. For example, power over land-use planning is largely local, but the forces shaping urban development patterns run the gamut from local to global (Glaeser and Kahn 2010; Salkin 2009; Stone Jr. 2009). Although U.S. federal agricultural policy plays a large role in setting incentives and policy priorities (Klyza and Sousa 2008), there is no equivalent mechanism for cities (Barnes 2005). Governance also can be driven in a more "bottom-up" fashion, as local actors and organizations seek to challenge prevailing power and authority sources that sustain existing carbon-related practices (Geels 2014; Seyfang and Smith 2007; Shove and Walker 2010).

The institutional arrangements of governance—the sets of rules, norms, and shared practices that underlie decisions—also differ among energy, urban areas, and agriculture. Institutional arrangements vary among these sectors in ways that have important consequences. Institutions may allow for greater or less public participation and engagement

from the private sector. Differences in institutional arrangements have implications for accountability of decision making and the sets of preferences and incentives shaping decision making. For example, accountability in urban governance typically lies with local elected officials—city councils and mayors—while accountability in energy production often lies with private utilities operating under widely varying mandates.

Finally, the sets of stakeholders involved in and implicated by the governance of energy, urban areas, and agricultural systems differ in terms of their priorities and position. Farmers' priorities may be entirely different from—even at odds with—those of regional energy companies or urban planners. Even within the U.S. federal bureaucracy, different agencies operate under very different sets of priorities and occupy very different positions in relation to congressional committees and regulated stakeholders; these priorities and positions may change from one presidential administration to the next. Understanding who governance stakeholders are and their priorities and positions is important for understanding carbon cycle dynamics.

6.3.3 Open Questions and Applications for Carbon Cycle Research

The differences and intersections inherent in these three sectors—agriculture, urban, and energy—mean that the path to understanding and improving governance of the carbon cycle requires knowledge of both the particularities of the different realms and the ways in which they reinforce and undermine one another. In particular, there is a need to incorporate a carbon cycle lens in research on their governance. A key area for future research will be shifting from a focus on individual policy tools (e.g., carbon pricing and energy efficiency incentives) to understanding how governance arrangements (i.e., in terms of their power structures, institutions, and stakeholder sets) shape the carbon cycle by encouraging or inhibiting energy conservation and carbon emissions reductions. Issues of fragmentation (e.g., multiple sources of partial authority) and misaligned incentives (e.g., low prices for energy supplies with large social costs) are likely to be pervasive. Another important area to examine is how emerging climate change governance arrangements (e.g., emissions trading schemes, renewable portfolio standards, urban plans, and land-management systems) interact with energy, urban, and agricultural governance systems, individually and together. Given the policy and political intersections among these realms, a focus on reducing carbon emissions may serve as an organizing force for effective carbon governance.

Despite the differences in how energy, urban areas, and agricultural systems are governed, these systems share a set of governance needs to effectively and sustainably govern carbon. All three systems require adaptability and resilience, coordination among sectors and scales, and a reorientation toward conservation and, ultimately, reducing carbon emissions (Bomberg et al., 2006; Voß and Bauknecht 2006). Research should continue to explore and identify patterns of coordinated governance among these realms and opportunities for greater coordination.

Finally, carbon governance research will benefit from more explicit attention to understanding which governance arrangements perform best according to a range of criteria.

6.4 Carbon Scenarios Embedded in the Future

Scenarios have long been used as fundamental tools to explore alternative future trajectories for the evolution of GHG emissions and atmospheric concentrations. Their development and application have spanned both quantitative and qualitative efforts to anticipate likely carbon futures, capture uncertainty in long-term carbon pathways, and establish alternative visions for the future. For example, over the past 25 years, the research community has developed and used the following as important research tools: 1) Intergovernmental Panel on Climate Change (IPCC) IS92 scenarios (IPCC 1990; Leggett et al., 1992); 2) the *IPCC Special Report on Emissions Scenarios* (SRES; IPCC 2000); and 3) most recently, Representative Concentration Pathways (RCPs; Moss et al., 2010). Such scenarios played

an important role in carbon cycle and global change research through their use as forcings for Earth System Models to estimate future changes in the physical climate system. As such, they have tended to have limited representation of the underlying socioeconomic conditions that generate the physical forcings. For example, the IS92 scenarios and RCPs are limited to concentration and atmospheric forcings of carbon dioxide (CO_2) and other GHGs. The scenarios from SRES, however, were associated with broader qualitative storylines regarding future global development, although the quantitative elements were limited to population and gross domestic product (GDP). Furthermore, the global nature of the storylines limited national, regional, or local articulation of development trajectories (Absar and Preston 2015).

In addition to their use in global change research, scenarios and scenario planning are frequently used within the private sector to explore the implications of alternative future energy, policy, and socioeconomic conditions. Shell is considered a pioneer in scenario planning for energy and climate. In 2013, Shell published *New Lens Scenarios*, which outlined technology and economic pathways to net zero carbon emissions by the end of this century (Shell 2013). More recently, Shell published *Shell Scenarios: Sky*, describing a pathway for delivering on the goals of the Paris Agreement (Shell 2018). Similar scenarios have been developed by other energy companies and trade associations (ConocoPhillips 2012; IPIECA 2016; BP 2018). Similarly, relevant energy and climate scenarios from national and international energy agencies include the U.S. Energy Information Agency's *Annual Energy Outlook* (EIA 2018) and the International Energy Agency's *World Energy Outlook* (IEA 2017).

Recent developments in global change research have recognized the importance of having a richer set of socioeconomic scenarios to better understand the alternative pathways by which societal development can lead to different emissions outcomes (van Ruijven et al., 2014), as well as how development can enable or constrain responses to manage risk inclusive of GHG mitigation, climate adaptation, and sustainable development. To this end, a scenario process complementary to RCPs is represented by the Shared Socioeconomic Pathways (SSPs; O'Neill et al., 2017). The SSPs consist of a set of five narratives that represent different combinations of challenges to mitigation and adaptation as well as quantitative scenarios at the national level for demography, GDP, and urbanization. Together, the RCPs and the SSPs represent the "parallel scenario process" (Moss et al., 2010), which was designed to reduce the time needed to develop scenarios for research and assessment. The RCPs enabled the climate modeling community to proceed with new simulations without waiting for bottom-up development of underlying socioeconomic conditions.

An ongoing process for the global change research community is to further elaborate and extend the SSPs to make them more useful for a broader range of social, economic, and policy research (Absar and Preston 2015; van Ruijven et al., 2014). This has included efforts to develop nested storylines for more regional analyses (Absar and Preston 2015) and to extend scenarios to address public health (Ebi 2013), as well as developing additional quantitative scenarios of other indicators (van Ruijven et al., 2014) such as poverty (Hallegatte et al., 2016). Additional effort is being invested in exploring how the SSP framework can be aligned to the Sustainable Development Goals (United Nations 2015).

A key SSP goal is to provide a flexible socioeconomic scenario framework that can be used by the global change community for diverse investigation and applications across multiple spatial and temporal scales. In particular, by integrating SSPs with RCPs, researchers can explore the development pathways that are consistent with alternative GHG concentrations, the climate implications of those concentrations, and the socioeconomic consequences of climate change, as well as mitigation, adaptation, and development policies (Kriegler et al., 2012; van Vuuren et al., 2014). In addition, opportunities exist to broaden the use of scenarios in global change research to include consideration

for normative questions such as, "What are the futures that various people want?" and "How can they be achieved?"

6.5 Vulnerability and Embedded Carbon

Because carbon is embedded in social, economic, political, and cultural arrangements, people are vulnerable to disruptions in the carbon cycle as changes in it bring changes in these social arrangements. Thus, research that first explicitly connects societal capacities, functions, and activities to carbon and then demonstrates the extent of human vulnerabilities will help to define ways to reduce those vulnerabilities. This is an alternative framing (see Section 6.1, p. 265) to vulnerability research and assessment that developed out of a framing that begins with physical changes to the carbon cycle and to climate and considers physical impacts first. (Using the physical science framing, researchers assess the vulnerability of agricultural crops and systems, species survival, future biodiversity, and ecosystem damage.)

In a framing of vulnerability assessment that investigates the potential for harm to human systems—by climate change and, by extension, the carbon cycle sources and sinks—researchers explore questions about who is likely to be harmed by climate change, how much harm is likely, compared across countries or areas, and the sources of vulnerability (exposure, sensitivity, and lack of adaptive capacity; Malone and Engle 2011). Comparative studies may aim to identify priority areas for governmental or donor investments in adaptation activities, while studies that include stakeholders may outline mitigation or adaptation activities and practices that stakeholders themselves are interested in undertaking.

6.5.1 Methods Used in Vulnerability Assessment

Researchers have used two broad approaches. The first is to select indicators of vulnerability and proxy variables (usually quantitative data) that represent those indicators and then to calculate comparative indices. The second approach is tailored to a locality by convening stakeholders and asking them to identify vulnerabilities, perhaps along with developing adaptive strategies or evaluating those already in use.

Studies have used indicators, case studies, analogies, stakeholder-driven processes, and scenario-building methodologies, sometimes employing mapping and geographic information system (GIS) techniques. These approaches often are combined to improve a given regional vulnerability assessment, and risk assessment is sometimes coupled with vulnerability assessment (Preston et al., 2009).

Stakeholder involvement has been particularly important in improving both vulnerability assessments and the design of adaptive responses (Rosentrater 2010). The community of stakeholders, whether in a village or a much larger region, then identify their community's vulnerabilities and how to address them using scenarios of the future that stakeholders develop based on relevant data, values and priorities, and realistic descriptions of what is feasible (de la Vega-Leinert and Schroter 2010; see Ch. 18: Carbon Cycle Science in Support of Decision Making, p. 728; Shaw et al., 2009; UKCIP 2001, 2005). Stakeholder involvement has been used in Canada (Carmichael et al., 2004) and the United States (NAST 2000) to build scenarios of the future.

6.5.2 Application to Carbon Cycle Research

The techniques of vulnerability assessment are well established, but the carbon cycle typically has not been part of research designs or indicators. Examples of studies that do not specify carbon cycle indicators include global vulnerability studies, in which Canada and the United States usually are ranked as having low vulnerability to climate change, whereas Mexico is ranked as having higher vulnerability (e.g., Yohe et al., 2006; Malone and Brenkert 2009). Also, subnational vulnerability studies identify economic activities and livelihoods directly related to carbon. A study of farming in Arizona (Coles and Scott 2009) showed that farmers have good access to information, notably seasonal climate forecasts, but consistently use proven short-term strategies rather

than take the large risks of changing farm animals or taking on the high cost of wind or solar energy. Furthermore, the assumption of rational decision making "ignores important influences such as tradition, identity, and other non-economic factors" (Coles and Scott 2009). Safi et al. (2012) found that rural Nevadans' risk perception of climate change is not affected by the sum of physical vulnerability, sensitivity, and adaptive capacity, but rather by "political orientations, beliefs regarding climate change and beliefs regarding the impacts of climate change" (Safi et al., 2012). For Mexico, Ibarrarán et al. (2010) assessed vulnerabilities to climate change at the state level, using comparative proxy variables; differences among the sources of vulnerability in the coming decades suggest different strategies for mitigation and adaptation. Ford et al. (2010) assessed the social factors in health-related Aboriginal vulnerability in Canada, finding that vulnerability is affected by poverty and inequality, limited technological and institutional capacity, sociopolitical beliefs, and lack of information. Furthermore, these elements of vulnerability are unevenly distributed among Aboriginal populations in Canada.

Bringing carbon considerations into vulnerability assessments has the potential to improve priorities for activities to address carbon cycle–related issues and the information base from which carbon cycle–related decisions can be made. For example, research into vulnerability that includes the carbon cycle can examine the specific implications of 1) depleted soil carbon and forest destruction in the agricultural sector; 2) the benefits of urban agriculture and methane capture for waste; and 3) the impacts of increased heat-trapping from excess CO_2 in the atmosphere (i.e., excess over what is being captured by plants, the ocean, and other sinks). This explicit inclusion of carbon can help stakeholders, who can more easily track the carbon content embedded in societal activities, as identified in vulnerability studies, than they can the more abstract long-term changes in climate. Understanding vulnerability to changes in the carbon cycle allows specific actions to reduce vulnerability by controlling emissions and capturing or conserving carbon.

6.6 Socioecological Systems and Embedded Carbon

Drawing on the seminal work of Holling (1973) to analyze complex adaptive systems and explore their resilience, researchers define socioecological systems as "nested, multilevel systems that provide essential services to society such as supply of food, fiber, energy, and drinking water" (Berkes and Folke 1998). They seek to answer research questions such as 1) What are the connections and dependencies between ecological and social systems (Berkes et al., 2003; McGinnis and Ostrom 2014)? 2) Why are some socioecological systems sustainable, or resilient, and some are not (Cole et al., 2013; Leslie et al., 2015; Ostrom 2009; Pahl-Wostl 2009)? Binder et al. (2013) describe 10 of the frameworks for conducting research on socioecological systems that include change dynamics, but the common goal is to include both social needs and the elements that create and support ecological production that, in turn, supports human beings. Interlinkages, feedbacks, and dynamics can be represented.

6.6.1 Methods Used to Analyze Socioecological Systems

Researchers who investigate socioecological systems and their resilience employ frameworks and models, often presented in network diagrams with or without multiple levels. Data may be gathered from published research, surveys, and interviews with stakeholders. Studies can be highly theoretical or focused on specific areas or systems. For instance, Cox (2014) analyzed the socioecological system of the Taos Valley Irrigation System in northern New Mexico, finding that the multilevel governance structure and the social networks have made the whole system stable and resilient. The study concludes that many factors "are needed in order to sustain complex [social-ecological systems] over time. Moreover, it is important to understand the relationships among the contributing factors. This complexity and interconnectedness would argue against the highly simplified approaches to environmental and development policy analysis that have persisted in scholarship and practice" (Cox 2014).

6.6.2 Application to Carbon Cycle Research

Applying this approach to an integrated analysis of the carbon cycle–and–human society system results in analysis of carbon as part of the configuration that supports humans with livelihoods and daily living activities. This integrated approach sets up a solution space that includes wider alternatives than those achieved simply by reducing emissions through substituting technical fixes; it can explore co-benefits (e.g., health and efficiency) that could more easily lead to action. Formulating questions such as those about people and the carbon embedded in their lives brings in considerations such as urban design, improved health, more leisure time, simplified life arrangements, and more cohesive communities.

6.7 Sociotechnical Transitions and Embedded Carbon

Reducing the anthropogenic influence on the carbon cycle implies transformative changes in sociotechnical systems. Therefore, an important issue is to understand why technological change comes about and whether or not change can be steered and accelerated.

The dynamics of sociotechnical changes and possibilities for managing them are studied in the field of sociotechnical transitions. Technologies (including those that use carbon) are deeply embedded in social practices, regulatory and market rules, landscapes, and values; the technical cannot be divorced from the social. This is a dramatic departure from traditional studies of technological change or innovation. One important assumption of sociotechnical transitions research is that greater improvements in eco-efficiency can be achieved through system innovation rather than by system improvement (see Figure 6.2, this page; Vollenbroek 2002). Systems innovation refers to alternative systems of energy, mobility, agro-food, and the closing of material loops (Geels 2002; Grin et al., 2010; Rotmans et al., 2001; Vollenbroek 2002).

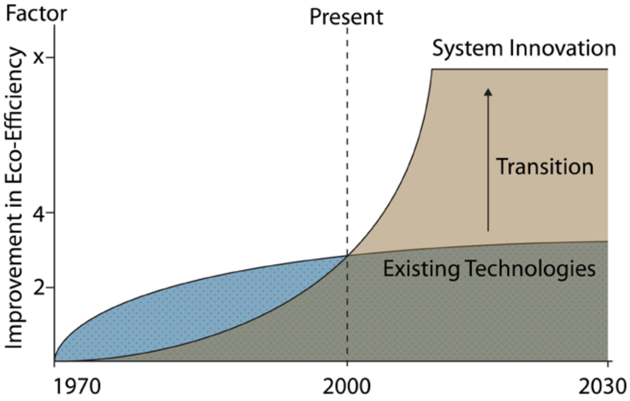

Figure 6.2. Insufficient Improvement of Existing Technologies to Meet Environmental Goals. Greater improvements in eco-efficiency can be achieved through system innovation rather than by system improvement. [Figure source: Redrawn from Vollenbroek 2002, copyright Elsevier, used with permission.]

Patterns of sustainability transitions are identified by Geels and Schot (2007) and de Haan and Rotmans (2011) and reviewed by Markard et al. (2012). Two foundational models for managing sociotechnical system changes are strategic niche management (Kemp et al., 1998) and transition management (Kemp 2007, 2010; Loorbach 2007; Rotmans et al., 2001). The model of transition management was developed in a project for the government of The Netherlands, based on a science-policy dialogue, details of which are described in Kemp and Rotmans (2009) and further developed by Loorbach (2007).

Transition management seeks to create system innovations through a model of guided evolution. Acting as a process manager, government mobilizes the interests of industry and society in system change with sustainability benefits (Kemp et al., 2007). Transition management methodology comprises the following elements (Meadowcroft 2009):

- Making the future more clearly manifest in current decisions by adopting longer time frames, exploring alternative trajectories, and opening avenues for system innovation, as well as system improvement;
- Transforming established practices in critical societal subsystems within which unsustainable practices are deeply embedded;

- Developing interactive processes where networks of actors implicated in a particular production-and-consumption nexus can come together, develop shared problem definitions, appreciate differing perspectives, and above all develop practical activities;

- Linking technological and social innovation because both sorts of change are necessary if society is to move to a more sustainable pathway;

- “Learning-by-doing,” developing experiments with novel practices and technologies because only by initiating change can societies learn the potential, and the limits, of different approaches;

- Tailoring support for technologies to different phases of the innovation cycle;

- Encouraging a diversity of innovations (i.e., variation) and competition among different approaches (i.e., selection) to fulfill societal needs; and

- Assigning an active role to government in mobilizing society to orient change in desired directions.

The visions for the future and details of policy are determined by political leaders, legislative bodies, and voter preferences, not by special agencies. The commitment to long-term change helps to orient state politics more toward system innovation. Government thus responds to calls for change from people and organizations by nurturing new technologies and, once these are better developed, supporting them more actively through diffusion policies. The availability of well-developed alternatives will give policymakers an easier path to introduce policy instruments such as carbon taxes and to phase out carbon-based technologies.

Analytically, the sociotechnical transition perspective examines interaction effects (i.e., coupled dynamics) among actors, technologies, rules, and institutions in evolving landscapes, as the broader context of sociotechnical regimes and niches of radical change. Such interactions give rise to four distinct transition patterns: substitution, transformation, reconfiguration, and de-alignment and re-alignment (Geels and Schot 2007). Specific pathways depend on structural landscape factors that shape action possibilities. Such factors include the presence of a strong and well-organized civil society with active cooperatives, citizen groups, activities, and socially engaged scientists; the salience of environmental issues in politics; and the industrial base for producing eco-innovations—all factors that were stronger in Germany than in the United Kingdom (Geels et al., 2016). In transition processes, no one is in control, and the interaction among different developments gives rise to outcomes that enhance the position of certain actors and technologies. New circumstances and counter strategies from incumbents, however, may change the trajectory.

The sociotechnical perspective emphasizes 1) the centrality of actors, while also being mindful of material aspects (e.g., in the forms of material interests, technologies, and infrastructures), 2) hybrid systems (e.g., decentralized technologies integrated into centralized systems), 3) spillovers from sectoral developments and various policy agendas, and 4) the duality of agency and structure. Attention to niche actors and landscape factors helps researchers to understand the demise of sociotechnical regimes such as in a substitution pathway and their gradual transformation in the three other pathways.

Under transition management approaches, societal interests in alternative technologies and system change are exploited in ways that fit with local circumstances. Transition thinking helps policymakers and actors in society to undertake useful actions in the forms of transition experiments, creation of transition platforms, and use of monitoring systems for managing the energy transition and the transition to the circular economy. These activities complement policies such as carbon taxes, regulations and soft obligations that constitute the Paris Agreement approach (Rajamani 2016), and national sustainable energy policies.

Laws and the embedding of transition endeavors in institutional frameworks help in pursuing transitions but are no guarantee of success. Research indicates that sustainability transitions require both control policies, pursued with rigor and perseverance, and innovation-support policies (Ashford and Hall 2011). Transition endeavors are likely to encounter opposition from incumbent actors, which can be observed in every transition process.

6.8 Carbon Connections in Social Networks

Social network analysis maps the connections among people who have links to one another. The focus is on the nature and strength of the links instead of on any characteristics of the individual members of the network. Examples of links relevant to the research include 1) "gives information to/receives information from," 2) "has a similar worldview," 3) "shares resources with," or 4) "is a coauthor of." Mapping the social network can provide insights about leadership and power structures.

6.8.1 Methods Used in Social Network Analysis

Social network analysis starts with a matrix drawn usually from a survey that shows the links among members of a defined social network. Software is used to both determine and display the linkages found, often with their strength, and to measure such characteristics as important nodes (i.e., centrality), density (i.e., out of the possible links, what is the proportion that actually exists?), and the length of certain pathways (e.g., through how many nodes must information go to get from one person to another?).

6.8.2 Applications to Carbon Cycle Research

Current relevant work, with few exceptions, does not focus on carbon but rather on climate change and disasters. Broadbent studies policy networks in the Comparing Climate Change Policy Networks project known as COMPON (see Broadbent and Vaughter 2014), which has teams in the United States, Canada, and Mexico (among other countries). Armitage et al. (2011) used social network analysis in case studies of co-management institutions for Canadian Arctic fisheries, finding that, over time, these networks co-produce knowledge, drawing on scientific and indigenous sources, that enables learning and adaptation. Malone (2009) used social network analysis to find shared elements of arguments (e.g., worldview, types of data used, authorities used, and solutions proposed) in the climate change debate, finding multiple connections even among analysts who make different arguments. Researchers also have studied disaster-response networks (Kinnear et al., 2013; Robins et al., 2011), where trust is a significant element in coordinated activity. Concerns about carbon link researchers and decision makers in complex networks, but these networks have not been mapped.

6.9 Social Practices and Carbon Configurations

The social practices perspective (Shove et al., 2012) offers a potentially useful approach to the needed "integrated models" discussed in Section 6.2, p. 268. As noted, the focus of U.S. demand-side energy policy has been on improving the efficiencies of devices, with limited attention to energy users, their energy uses, or the social shaping of energy consumption (Lutzenhiser 2014). Similarly, Mexico's Energy Reform program has targeted the technical aspects of equipment, appliances, and energy consumption in public buildings, rather than a more systematic view that starts with a framing of meeting people's needs for energy in low-carbon ways (Valdez 2015).

The social practices perspective takes a more explicit social sciences–based approach to understanding energy use and carbon emissions, offering new ways of seeing complexity and understanding the possibilities for change in social patterns of consumption. Rather than focusing on technologies, behaviors, and desires, for example, as relatively independent, this perspective takes "practices" as the object of inquiry, highlighting how daily living rests on dependencies among people, activities, technologies, and supply

systems, as well as how the various practices relate to each other. It thus involves appreciating the social origins of taken-for-granted "needs" for particular goods and services, which, in reality, vary considerably across time, space, and populations. By not assuming that patterns of activity—human interactions with technologies or current levels of energy use—are fixed or unquestionable, the practices perspective can lead to rethinking housing, transportation, home-workplace relationships, lifestyles, technology designs, and policy approaches.

Social practice theory applied to energy use and carbon emissions draws on several overlapping strands of contemporary research. One strand is sociological theory concerned with how social structures come into being and are reproduced at multiple scales—from the individual to the group, social institutions, and macro-organization within and between societies in the global system (e.g., Giddens 1984). A second is an appreciation that social actors' household habits and routines involve ongoing skilled cultural interactions with technological artifacts and sociotechnical systems (Lutzenhiser 1992). The third recognizes that actors' and households' understandings of their own energy-using activities are important to grasp as they are expressions of larger institutional beliefs and knowledge systems (Shove et al., 1998). Together, the strands focus attention on the systematic interactions among human actors, devices, meanings, skills, infrastructures, and social systems—compared to the more traditional focus on elements in relative isolation (e.g., behaviors, needs, and appliances) that was common in earlier research on energy use and energy efficiency.

Examples of social practices include cooking and eating, driving, walking, riding, using personal and family electronic devices, heating and cooling, washing, entertaining and visiting, and home buying and renovating. While their expression can vary considerably within societies, by definition social practices are not idiosyncratic; they are shared and maintained by social groups. Practices are patterned and clustered with other practices. They often are taken for granted but can become problematic and subject to criticism (e.g., use of water on lawns in drought areas, driving cars short distances for errands, and wearing business suits in the summer in Japan). Practices have histories; they change over time, and they are bundled with physical materials and technologies in mutually supportive relationships. They are sometimes discarded but also can persist long after the conditions that gave rise to them have changed; discarded practices also can be subsequently revived and adapted. In this view, all carbon emissions are produced as a by-product of social practices—and social practices are produced within a complex of social circumstances, rather than by isolated free will.

The importance of beginning research by analyzing these practices to assess the "social potential" (Shove et al., 2012) of interventions in the carbon cycle follows from the fact that, while most energy use and carbon emissions themselves are invisible to the people and groups responsible for them, they are embedded in immediately meaningful social patterns and norms. Therefore, practices often are locked in by shared habits and expectations that require the use of particular devices (e.g., appliances, automobiles, and office buildings) that, in turn, depend on the energy flows and emissions of the larger sociotechnical systems to which they are connected. And these larger systems prove to be incredibly complex, made up of linked technologies and infrastructures, codes and regulations, organizational structures and networks, geographies, and shared scientific and technical knowledge frameworks (Bijker et al., 1987).

Thus, the social practice theory view appreciates this complexity and concludes that what people do with their lives—how they live and relate to others—has considerable salience and importance for carbon emissions reduction, and largely abstract calls for change should be met with skepticism. As a general rule, changes in practices should be expected to be hard to achieve as a policy or market goal, and the hoped-for "levers" of change in practices may well demand coordinated action on interconnected elements of social, technical, political, cultural, environmental, and economic systems. Nonetheless, changes

in practices are continually occurring, sometimes in directions that seem "desired" from the perspective of climate change goals and policies. Funding from European scientific and energy agencies is being directed toward understanding the evolving carbon-emitting practices of households and organizations, with attention to origins, dynamics, interdependencies, and trends—including the effects of innovations in technology and policy on changes in social practice (DEMAND 2016; RCUK 2016).

6.10 The Roles of Communication and Stakeholder Involvement

Although people generally respect science and scientific findings, the so-called science-policy gap persists. The gap appears when scientific findings that seem to call for policy action are not taken up by policymakers in expected ways. Thus, renewed attention has been focused on how to communicate scientific findings to facilitate their enaction. Communicating scientific findings can be ineffective depending on the subject matter, the framing used, and the ways in which messages are delivered. What people choose to believe is heavily influenced by their political environment (Lupia 2013) and by religious or political beliefs (Nisbet and Scheufele 2009). For example, if science reaches consensus on a new rocket technology, there is little question from the public about its legitimacy. On the other hand, if observations and analyses are contrary to political messaging or bring into question belief systems, scientific information can be quickly discounted. Research has been conducted to understand this phenomenon in an effort to identify core issues and a path forward for effectively communicating science.

Initial indications are that cultural and peer-group dynamics are more influential than science literacy and the communication of scientific evidence (Kahan et al., 2012). A follow-up study used a different set of questions to rate "open-mindedness" of individuals and found that the metric only reinforces and accentuates existing beliefs (Kahan and Corbin 2016). Similarly, a comprehensive review of 171 studies from 56 nations found that acceptance of climate change science is more strongly predicted by cultural variables such as ideology and political orientation than by demographic variables including age, gender, income, and ethnicity (Hornsey et al., 2016). More research is needed to understand how individuals assimilate knowledge, particularly if it runs contrary to cultural or peer-group influences. Results from this research might be useful in guiding alternative ways to communicate carbon cycle science results more effectively.

Based on the more recent findings of science knowledge assimilation, frameworks for science communication continue to evolve. New models of science communication have been proposed that would require a coordinated effort to identify questions, conduct research to address the questions, and understand how to best communicate the answers in a robust and supported manner (Pidgeon and Fischhoff 2011). A contemporary definition of science communication outlines specific components that should be addressed when communicating science (Burns et al., 2003). A renewed look at how communication is occurring over social media and how science communication can adapt to the new media landscape has been suggested (Brossard and Scheufele 2013).

Research indicates that communicating consensus around science topics increases public acceptance of the findings, but that a process known as attitudinal inoculation may be needed to maintain acceptance (van der Linden et al., 2017). This process essentially consists of pre-emptively highlighting and refuting false claims and potential counterarguments, such as those made by climate change deniers (Oreskes and Conway 2011). False claims and intentional dissemination of misinformation on related science topics have been analyzed by the research community (Farrell 2016; Supran and Oreskes (2017). A concentrated focus on methods of science communication, based on current understanding of knowledge assimilation, will be critical to enabling the use of science for decision making. Likewise, renewed efforts on making science results more accessible and relevant to collective decision

making, using current communication technologies, are needed.

Many of these research studies examine one-way communication: from scientists to audiences including policymakers, business people, and the general public. Another form of communication, stakeholder involvement—a standard social scientific method—helps researchers and decision makers to address issues and agree on actions (O'Connor et al., 2000; Fiack and Kamieniecki 2017). Mutual exchanges among stakeholders (policymakers and others involved in carbon-relevant decisions) bring to light people's values, concerns, and sticking points and allow dialogue needed to establish feasible options and implement programs. Stakeholder involvement typically identifies co-benefits of reducing emissions; multiple benefits help to gain widespread acceptance. Examples include changes that bring benefits such as reduced air pollution with associated health benefits or new jobs in renewable-energy industries. Other benefits could include amenity improvements from increased urban tree cover, more efficient heating and cooling systems, the convenience of "walkable" neighborhoods, and the safety of buildings that can withstand high winds and flooding.

What may emerge in stakeholder-science-policy dialogues are gradually increasing levels of agreement on issues as well as a variety of options for action. People in direct communication may discover that they are arguing from different viewpoints; missing practical concerns or obstacles; and/or that they actually agree within a mutually defined framing of problems, solutions, or both (Hulme 2009; Malone 2009).

Stakeholder involvement and associated communication exchanges between scientists and decision makers improve the likelihood that pathways forward can be identified, adopted changes will be implemented, and that further changes will be adopted over time.

6.11 Opportunities to Reduce Carbon Emissions

Because changes in social, institutional, and technological structures and practices result from people's decisions to change, the opportunities to reduce carbon emissions are broad-ranging. This section will focus on opportunities for behavioral and institutional changes as described in the research literature.

The IPCC (Blanco et al., 2014) summarized the state of social and behavioral sciences research:

"There are many empirical studies based on experiments showing behavioural interventions to be effective as an instrument in emission reductions, but not much is known about the feasibility of scaling up experiments to the macro economy level. …The net effect of trade, behaviour, and technological change as a determinant of a global increase or decrease of emissions is not established." (Blanco et al., 2014)

Obvious pathways to explore in efforts to reduce carbon emissions are to change individual and group behaviors—for instance, to dial down thermostats, drive and fly less, buy energy-efficient appliances, eat less meat, and plant trees. Dietz et al. (2009) estimated the behavioral potential of these kinds of changes. They found that "the national reasonably achievable emissions reduction (RAER) can be about 20% in the household sector within 10 years if the most effective nonregulatory interventions are used. This amounts to 123 metric tons of carbon (Mt C) per year, or 7.4% of total national emissions" (Dietz et al., 2009). Actions included home weatherization, upgrades of heating and cooling equipment, more efficient vehicles and home equipment, equipment maintenance and adjustments, and daily use behaviors.

Stern et al. (2016) point out that interventions must "take into account key psychological, social, cultural and organizational factors that influence energy choices, along with factors of an infrastructural, technical and economic nature. Broader engagement of social and behavioral science is needed to identify promising opportunities for reducing fossil fuel consumption" (Stern et al., 2016). These researchers then describe short-term, intermediate, and long-term changes that could reduce fossil fuel consumption (FFC). Table 6.1, p. 286, is adapted from a portion of their table that listed actions for

Table 6.1 Changes to Reduce Fossil Fuel Consumption at Various Social and Temporal Scales[a,b]

Social Scales and Roles	Temporal Scales		
	Short-Term Actions (Moments to Days)	**Intermediate Actions (Weeks to Decades)**	**Long-Term Actions (Generational, Transformational)**
Organizations as energy consumers	Induce employees to reduce energy use (e.g., in offices, minimize use of task lights, computers, auxiliary heating and cooling devices). Reduce motorized business travel (e.g., by using video conferencing). Assign staff "energy champion" responsibilities. Manage production systems in response to real-time price signals.	Make reducing fossil fuel consumption (FFC) a strategic part of core business operations. Replace lighting and HVAC systems, equipment, and motor vehicles with energy-efficient models. Rent or procure low-FFC buildings when relocating. Adopt photovoltaic systems. Change work styles to accommodate a broader range of thermal conditions (e.g., Japan's Super Cool Biz program).	Change core business offerings to align with climate challenges (e.g., BP's short-lived "beyond petroleum" experiment, or Interface Carpet's goal of carbon neutrality).
Organizations as providers of goods and services	Find lower-footprint supply sources. Inform customers on how to use products and services offered in an energy-efficient way. Reduce FFC in the production chain.	Make reducing FFC a strategic part of core business offerings. Support and train staff in systems thinking and sustainability. Redesign products for lower energy requirements. Elect to manufacture, market, and service low-FFC products.	Develop lower-carbon, industry-wide standards (e.g., carbon labeling schemes for suppliers).
Large-scale social systems	Improve crisis responses to power outages and fuel shortages.	Adopt policies to encourage and assist lower-FFC actions in households and organizations. Create institutions and norms for lower-FFC actions in groups of organizations.	Improve public transport system. Design communities for easier nonmotorized travel. Change norms for socially desirable housing, vehicle types, workstyles, and work practices.

a) Adapted from Stern et al., 2016.

b) Key: FFC, fossil fuel consumption; HVAC, heating, ventilation, and air conditioning.

organizations (i.e., consumers and producers) and large-scale social systems.

6.12 Conclusions

6.12.1 Research Insights

Findings from these lines of research draw on scientific knowledge about social change, the role of science in societies, multilevel governance, and social-psychological behavior in many settings. The following research findings and insights reflect the people-centered framing discussed throughout the chapter and hold promise for future exploration.

People-Centered Research. Research that is framed to begin with people and explore how various social, political, and economic configurations and technologies have carbon embedded in them reveal points of intervention that are practical and feasible.

Expanded Use of Data. "Big data" and associated data-mining activities related to social segments, lifestyles, and purchasing and activity patterns could significantly expand relevant knowledge about people, social systems, and embedded carbon.

Analysis of Real-Life Decision Making. Understanding how people really decide and change requires questioning, observing, and interacting; decision makers rarely make ideal, completely rational decisions.

Invisibility of Energy and Emissions. Energy consumption and emissions are part of people's routines and habits, within patterns of social interaction, and are governed largely by social norms and expectations—without regard for or reference to (out-of-sight) energy sources or carbon emissions resulting from these activities.

Shared—and Varied—Patterns of Energy Use. Energy-using activity patterns are shared within groups, stabilized and constrained by energized technologies and infrastructure; large variations are seen in different groups, across populations (e.g., of households or firms), and over time as people modify and adapt.

Relative Unimportance of Cost Motivations. Environmental values, social influences, and concerns for others are more frequent and actionable motivations for carbon-reducing equipment purchases and energy-use behaviors than are potential cost savings.

Deeper Understanding of Consumer Behavior. Although the energy-efficiency industry tends to assume that customers are rational in evaluating information, psychological research has shown that even well-informed social actors routinely pass over clear and simple "rational" choices that would save money by saving energy.

Success in Marketing Efficient Technologies. "Market transformation" research has been successful in identifying "upstream" actors and organizations in supply chains and engaging with technology designers, manufacturers, wholesalers, and retailers to encourage and facilitate bringing more efficient technologies to the marketplace at appealing prices.

Codes and Standards for Efficient Technologies. Efforts by some states and the U.S. federal government to regulate the energy-using characteristics of appliances and buildings through codes and standards have had wide systemic impacts on technology efficiency.

Importance of Considering User Behavior. "Behavioral potentials" for energy savings (e.g., in equipment-use patterns and practices) have become increasingly recognized. When planning efficiency improvements, utility regulators and efficiency advocates have added the consideration of what people actually do with energy-using equipment to the technology specifications.

Understanding and Modeling Complex Decisions. Capturing the complexity of carbon-relevant decisions to show effective and democratic paths to reduced carbon emissions could be accomplished through developing inclusive integrated models and increased understanding of the systems involved.

Improved Understanding of Governance Processes. To understand patterns of carbon emissions and, importantly, how to facilitate sustainable emissions trajectories, researchers and decision makers would benefit from increased understanding of the governance processes guiding emissions' production, maintenance, and conservation, leading to identification of feasible governance options for reducing carbon emissions.

Differences and Common Needs Among Governance Systems. The governance systems for the energy, urban, and agricultural sectors overlap and sometimes contradict one another; they differ from one another in three important ways: their sources of power and authority, their institutional arrangements, and the sets of their stakeholders engaged by governance processes. Despite the differences in how these systems are governed, they share a set of governance needs to effectively and sustainably govern carbon—needs to adapt, increase resilience, coordinate among sectors and scales, and reorient toward conservation and, ultimately, reducing GHG emissions.

Broadened Use of Scenarios. Opportunities exist to broaden the use of scenarios in global change research to include consideration for normative questions such as, "What are the futures that various people want?" and "How can they be achieved?"

Systems Analysis to Improve Options for Effective Action. Analysis of carbon as part of a socioecological system that supports humans with livelihoods and daily living activities sets up a solution space that includes wider alternatives than simply reducing emissions by substituting technical fixes; the socioecological approach can explore co-benefits (e.g., health and efficiency) that could more easily lead to action.

Technologies as Embedded in Social Systems. Technologies are deeply embedded in social practices, regulatory and market rules, landscapes, and values; the technical cannot be divorced from the social.

Needs for Both Policies and Markets. Well-developed systems are unlikely to be overthrown by new ones through market processes: sustainability transitions likely will be faster and more comprehensive with strong governmental policies in the form of a phase-out of unsustainable technologies. Research indicates that sustainability transitions benefit from control policies, pursued with rigor and perseverance, next to innovation-support policies.

Analysis of Social Practices. Daily living rests on dependencies among people, activities, technologies, and supply systems and how various social practices relate to each other. It thus involves appreciating the social origins of taken-for-granted "needs" for particular goods and services, which, in reality, vary considerably across time, space, and populations. By not assuming that patterns of activity—human interactions with technologies or current levels of energy use—are fixed or unquestionable, the practices perspective can lead to rethinking housing, transportation, home-workplace relationships, lifestyles, technology designs, and policy approaches.

Two-Way Communication. One-way communication of scientific findings is problematic (especially when people's values or beliefs seem threatened), but well-designed stakeholder involvement can result in mutually accepted actions.

6.12.2 Research Priorities

Carbon is embedded in myriad types of social-economic-political-cultural institutions and thus is involved in the interwoven systems that emit and sequester carbon. Human institutions include government, industry, energy, transportation, buildings, urban areas, land, agriculture, and households. The current state of the carbon cycle is, therefore, an extremely complex, although not intractable problem. Recognizing the social embeddedness of carbon leads to research that will deepen knowledge about how social systems both persist and change, indicating pathways by which carbon emissions can be reduced and carbon sequestration increased.

Although much valuable research is sector based and economically minded, social science researchers have gone beyond these types of research to develop approaches that focus on people and their social configurations—systems of systems—that have carbon embedded in them. This focus is important to assess uncertainties and the progress of mitigation and adaptation efforts. More and more, the challenge of carbon cycle research and management is to deepen basic understanding of how people are negotiating change in their own interests as they live and participate within organizations and institutions, according to constraints, opportunities, and values in specific situations. If people are to contribute to major reductions in carbon emissions, they also will modify their lifestyle choices in the name of what they may initially perceive as intangible or yet-unknown environmental benefits.

The research lines described in this chapter lend themselves both to interdisciplinary research and to stakeholder involvement in development of research questions, priorities of decision makers, and feasibility of proposed actions. Future research needs encompass a spectrum of approaches, as listed below, to increase understanding of people's decision making and change processes.

Theory and Data Gaps. Opportunities to better leverage existing social science datasets or approaches for climate and carbon research include the following:

- *Theory without data.* Potentially useful social science theories—including social survey–based analysis; ethnographic analysis; and narrative sources of insight into people's beliefs, understandings, and actions—have been applied only limitedly to climate change research.

- *Granular data on human activities currently applied almost exclusively for commerce.* In particular, big data and associated data-mining activities related to social segments, lifestyles, and purchasing and activity patterns could significantly expand relevant knowledge about people, social systems, and carbon. However, this potential has not yet been deployed or customized for climate change questions.

- *Data with little or no theory attached.* They include highly aggregated census data and utility billing data, which are common in policy analyses but lack information about users. Social sciences have had only limited involvement in such analyses.

- *Data analysis methods and the evaluation of scientific acceptability.* These approaches are not yet advanced enough to sync with the new worlds of data and types of issues to be addressed.

Recognition of the Social Nature of Energy Use. Future research and institutional changes would benefit from recognizing the social nature of energy use—including the social organization of technologies and energy systems, the social patterning of energy demands, the social nature of energy-conservation choices, and the social delivery of energy-efficiency programs and policies.

Broader Views of Governance. A key area for future research will be shifting from a focus on individual policy tools (e.g., carbon pricing or energy-efficiency incentives) to understanding how governance arrangements (in terms of their power structures, institutions, and stakeholder sets) shape the carbon cycle by encouraging or inhibiting energy conservation and reducing carbon emissions. Issues of fragmentation (e.g., multiple sources of partial authority) and misaligned incentives (e.g., low prices for energy supplies with large social costs) are likely to be pervasive.

Links Among Carbon Management and Other Governance Arrangements. Emerging climate change governance arrangements (e.g., emissions trading schemes, renewable portfolio standards, urban plans, and land-management systems) will interact with energy, urban, and agricultural governance systems, individually and together. Integrated research will represent these interactions.

Technological Transitions. Social scientific research provides better understanding of why transformative technological change comes about and whether or not change can be steered and accelerated in sociotechnical systems to lessen the anthropogenic influence on the carbon cycle.

Social Networks and Practices. Research can map social networks of relevant potential actors in carbon cycle research and mitigation activities and describe everyday practices in which carbon is embedded; both approaches can reveal potential pathways for carbon management.

Use of Existing Tools and Methods. Research that applies such developed methods as scenarios, vulnerability assessment, sociological systems, social network analysis, and social practices analysis to include the carbon cycle will highly complement physical science research by providing understanding of social perceptions of and engagement with aspects of the carbon cycle.

SUPPORTING EVIDENCE

Process for Developing Chapter

This chapter was developed as part of the overall process for initiating the *Second State of the Carbon Cycle Report* (SOCCR2). Although "societal drivers" were specified as a section in all chapters, the Federal Liaisons and Science Leads agreed that a separate chapter on relevant social science research was needed to strengthen the report and respond to the recommendations of the *First State of the Carbon Cycle Report* (SOCCR1). The chapter contents were developed through conference calls and discussions with comments from scientists, U.S. federal agency personnel, and the public.

KEY FINDING 1

Broadened Approaches—A range of social scientific research approaches, including people-centered analyses of energy use, governance, vulnerability, scenarios, social-ecological systems, sociotechnical transitions, social networks, and social practices, complements physical science research and informs decision making. Approaches that are people centered and multidisciplinary emphasize that carbon-relevant decisions are often not about energy, transportation, infrastructure, or agriculture, as such, but rather about style, daily living, comfort, convenience, health, and other priorities *(very high confidence)*.

Description of evidence base

For Key Finding 1, physical scientific research has produced extensive information on the so-called greenhouse effect, the overall warming of the global climate, and the contribution made to climate change by human-caused emissions of heat-trapping gases; studies of the carbon cycle have confirmed that carbon is being emitted to the atmosphere from human activities. Research that starts with this framing has quantified sectors and activities where mitigation of climate change is technically possible. Yet the ideal global policies, national commitments, and implementation of such policies have not taken place to the degree necessary to substantially reduce emissions. Relevant social science research is needed to understand feasible pathways to both mitigation and adaptation actions using a framing that is centered on people. This need has been increasingly recognized by the Intergovernmental Panel on Climate Change (IPPC) and other international, regional, and local organizations concerned with climate change. See Section 6.1, p. 265; Section 6.2, p. 268; and Section 6.11, p. 285, for a more detailed description of the evidence base and relevant citations.

Major uncertainties

Uncertainties include the degree to which societies are vulnerable to climate change, the systematic implications of various candidate actions and policies in specific places, and the capacity and willingness of human institutions and individuals to act.

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

Evidence from the existing body of social scientific research has identified feasible pathways to mitigation with very high confidence.

Summary sentence or paragraph that integrates the above information

There is very high confidence in Key Finding 1 that people-centered social science research can explore and demonstrate feasible and implementable mitigation strategies and actions.

KEY FINDING 2

Assumed versus Actual Choices—Planners have assumed economically rational energy-use and consumption behaviors and thus have failed to predict actual choices, behaviors, and intervening developments, leading to large gaps between predicted rates of economically attractive purchases of technologies with lower carbon footprints and actual realized purchase rates *(high confidence)*.

Description of evidence base

From large potential emissions reductions calculated by integrated assessment models to expected behavior changes encouraged by employers, results of first-best policies and programs have been disappointing at levels from the global to the local. See Section 6.2.2, p. 271, for a more detailed description of the evidence base and relevant citations. Even activities such as methane capture, which has been calculated to be economically profitable, have not been widely implemented by mining and other industries. Lifecycle calculations that show savings from energy-efficient technologies such as weatherstripping, insulation, and heating and cooling equipment have failed to prompt rational choices to increase energy efficiency or purchase energy-efficient homes in numbers near the technical potential. See Section 6.2.2, p. 271, and Section 6.9, p. 282, for a more detailed description of the evidence base showing the difference between predicted, economically rational decisions and actual decision-making processes.

Major uncertainties

Although much has been learned about such "market failures" or "barriers," the reasons for gaps between predicted and actual results encompass factors that are still uncertain in their specific roles and magnitudes.

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

Numerous studies have conclusively documented gaps between predicted or potential emissions reductions and actual choices and behaviors, leading to a very high confidence level.

Summary sentence or paragraph that integrates the above information

Science findings for Key Finding 2 demonstrate a very high confidence that planners should not assume rational behavior of people and organizations in acquiring more efficient technologies and using them efficiently

KEY FINDING 3

Social Nature of Energy Use—Opportunities to go beyond a narrow focus on the energy-efficiency industry to recognize and account for the social nature of energy use include 1) engaging in market transformation activities aimed at upstream actors and organizations in supply chains, 2) implementing efficiency codes and standards for buildings and technologies, 3) conducting research to understand how people's behaviors socially vary and place different loads on even the most efficient energy-using equipment, and 4) adding consideration of what people actually do with energy-using equipment to plans for technology and efficiency improvements *(high confidence)*.

Description of evidence base

Key Finding 3's four specific areas reflect current research that shows promising results from people-based approaches. Focusing on the systems involved in supply chains—technology

designers, manufacturers, wholesalers, and retailers—brings people and organizations together in a common purpose to facilitate and provide financial incentives to bring more efficient and less carbon intensive technologies and processes into an industry. Similarly, codes and standards for buildings and technologies create industry-wide benchmarks and so encourage sharing of knowledge and practices as well as competition to be efficient or meet a standard such as "Energy Star" (www.energystar.gov). The variations in human energy use by place and social condition have been well established, but people-based research showing why such variations exist and how they can be addressed needs to be expanded and strengthened. When planners include studies of actual energy-use requirements instead of technical potentials, the efficiency gap lessens or disappears—or, in some cases, actual emissions reductions are greater than predicted. See especially Section 6.2.3, p. 272, for a more detailed description of these research studies and relevant citations.

Major uncertainties

Uncertainties arise from the lack of needed social science research in these areas as well as from identifying other areas that would benefit from people-based research into carbon mitigation.

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

There are promising areas of research with positive results in at least four areas of energy efficiency, leading to an assessment of high confidence.

Summary sentence or paragraph that integrates the above information

Promising people-based research covered for Key Finding 3 exists as approaches to increase efficiency and thus reduce emissions along supply chains, implement codes and standards for buildings and technologies, understand the variation in energy use among groups and in different places, and include energy-use practices in planning for new technologies or processes. Thus, a level of high confidence is warranted.

KEY FINDING 4

Governance Systems—Research that examines governance at multiple formal levels (international, national, state/province, cities, other communities) as well as informal processes will identify overlaps and gaps and deepen understanding of effective processes and opportunities involved in carbon management, including a focus on benefits such as health, traffic management, agricultural sustainability, and reduced inequality *(medium confidence)*.

Description of evidence base

As global, "top-down," effective climate change or carbon management policy has proven elusive and likely not to meet goals, Key Finding 4 shows that attention has turned to governance (but not limited to formal governments), including networks, social processes, cultural norms and values, and multilevel steering institutions. In urban areas and agricultural spaces, this research has proven fruitful in identifying insights into how policies are formed and implemented as people pursue their own goals while changing in response to economic, regulatory, and other social changes. Research shows that co-benefits are often important—benefits such as health, traffic management, comfort and convenience, agricultural sustainability, and reduced inequality. See Section 6.3, p. 274, for a more detailed description of governance systems research and relevant

citations. Each place or network or governance arrangement is a complex system, but patterns can be discerned. Analysis of social, technological, and ecological circumstances can lead to tailored approaches and pathways to effective carbon management. See Section 6.6, p. 279; Section 6.7, p. 280; and Section 6.8, p. 282, for more detailed descriptions of the evidence base for Key Finding 4, as well as relevant citations.

Major uncertainties

Uncertainties arise from the diverse circumstances of places and societies. Research may not identify important factors in candidate strategies for carbon management, even with the knowledge that "one size does not fit all."

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

Research confirms the importance of governance. However, because of the complexity and diversity of different societies in different places, and at least the partial lack of research to identify patterns of governance important for carbon management, a level of medium confidence has been assessed.

Summary sentence or paragraph that integrates the above information

Both formal and informal governance are important for the prospects of carbon management. However, variations in social institutions, culture, and values influence the effectiveness of governance. Hence, the difficulties in complex systems analysis bring uncertainty into the prospects for effective carbon management. Thus, Key Finding 4 has been assessed as having medium confidence.

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7 Tribal Lands

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KEY FINDINGS

1. Many Indigenous peoples in North America follow traditional agricultural and land-use practices that govern carbon cycling on tribal lands. These practices include no-till farming; moving domesticated animals seasonally in accordance with forage availability; growing legumes and cover crops; raising crops and livestock native to ancestral landscapes; and managing forests sustainably with fire, harvest, and multispecies protection.
2. Scientific data and peer-reviewed publications pertaining to carbon stocks and fluxes on Indigenous (native) lands in North America are virtually nonexistent, which makes establishing accurate baselines for carbon cycle processes problematic. The extent to which traditional practices have been maintained or reintroduced on native lands can serve as a guide for estimating carbon cycle impacts on tribal lands by comparisons with practices on similar non-tribal lands.
3. Fossil fuel and uranium energy resources beneath tribal lands in the United States and Canada are substantial, comprising, in the United States, 30% of coal reserves west of the Mississippi River, 50% of potential uranium reserves, and 20% of known oil and gas reserves, together worth nearly $1.5 trillion. Fossil fuel extraction and uranium mining on native lands have resulted in emissions of carbon dioxide and methane during extraction and fuel burning. Energy resource extraction on tribal lands also has resulted in substantial ecosystem degradation and deforestation, further contributing to carbon emissions.
4. Renewable energy development on tribal lands is increasing but is limited by federal regulations, tribal land tenure, lack of energy transmission infrastructure on reservations, and economic challenges.
5. Colonial practices of relocation, termination, assimilation, and natural resource exploitation on native lands have historically hindered the ability of Indigenous communities to manage or influence land-use and carbon management both on and off tribal lands. These factors combined with contemporary socioeconomic challenges continue to impact Indigenous carbon management decision making.
6. The importance placed on youth education by Indigenous communities creates opportunities for future generations to sustain and pass on traditional knowledge important to managing carbon stocks and fluxes on native lands.

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

7.1 Introduction

"Indigenous peoples in North America have a long history of understanding their societies as having an intimate relationship with their physical environments. Their cultures, traditions, and identities are based on the ecosystems and sacred places that shape their world. Their respect for their ancestors and 'Mother Earth' speaks of unique value and knowledge systems different than the value and knowledge systems of the dominant United States settler society. … Some Indigenous people believe that human and nonhuman individuals come from the earth and the ability to reach harmony among individuals is dependent on being a steward of the natural environment by giving back more than what is taken" (Chief et al., 2016).

This chapter discusses how diverse Indigenous peoples in the United States, Canada, and Mexico affect and are affected by carbon cycle processes, and it explores the unique challenges and opportunities these communities have in sustaining traditional practices that are inherently tied to carbon stocks and fluxes on a range of landscapes. Carbon fluxes on tribal lands likely differ from those on analogous non-tribal land types (e.g., non-tribal forested, coastal, aquacultural, grassland, and agricultural lands) due to generations of Indigenous people

following traditional agricultural and land-use practices. These practices, referred to as "traditional knowledge," are rooted in an Indigenous worldview that holds humans responsible for the stewardship of all elements of the living and nonliving world around them. This chapter compares traditional agricultural, land-use, and natural resource stewardship practices with those introduced to North America by European settlers to estimate carbon fluxes on tribal lands relative to similar non-tribal land types.

Intrinsic differences in traditional and historical land-use practices on and off tribal lands can inform understanding of the carbon cycle and are the basis for considering tribal lands as a focused topic in this report. The lack of direct measurements of carbon stocks and fluxes on tribal lands requires that carbon cycle impacts associated with traditional practices be considered in comparison with non-tribal practices on similar land types, as data do not yet exist for creating tribal land carbon budgets. Formidable challenges resulting from the inclusion in this report of geographically and culturally diverse Indigenous peoples across North America are acknowledged. However, outlining opportunities for further exploration of traditional practices and how they could influence the carbon cycle is essential. Both the challenges and opportunities set the stage for identifying research needs that may empower Indigenous communities to expand their influence on decision making, affecting carbon management both on and off of tribal lands. Case studies are used to illustrate how traditional forestry, livestock, and crop production practices can impact carbon stocks and fluxes. Contributions to the carbon cycle from past and ongoing fossil fuel and uranium energy extraction and the role of renewable energy production on tribal lands also are covered.

7.1.1 Indigenous and Eurocentric Worldviews

The worldview of native communities (collectively referred to in this chapter as "Indigenous peoples") from the United States, Canada, and Mexico is ecosystem- and watershed-based, inextricably bound to the land, and thus intimately connected to ecological systems integral to the carbon cycle. Management of carbon stocks and fluxes is encompassed within, and not easily separated from, the overall Indigenous perspectives that holistically link human and ecological health. These perspectives fundamentally differ from the Eurocentric worldview introduced to North American landscapes with the influx and migration of European settlers across the continent. A meaningful (albeit simplified) contrast between Indigenous and Eurocentric worldviews underpins the different approaches tribal and non-tribal communities have toward living on the land, which, in turn, influences how they manage carbon stocks differently on similar land types. Indigenous worldviews are rooted in a communal, spiritual, and cultural sense of place built on a web of connections between humans (living and ancestral) and nature (animals, plants, and minerals). Traditional agrarian practices are based on significant horticultural advancements using grouped planting strategies. One example is the "Three Sisters" agricultural system of mound structures in the eastern United States, where the climate is wetter. Another example involves planting seeds deeply in sand in the arid, rainfed agriculture of the western United States. These practices are native to ancestral landscapes and ecosystems and have integral ties to ceremonial practices and seasonal cycles. In contrast, Eurocentric worldviews are more uniformly applied and were built on the notion of altering the natural world. Agricultural practices introduced to North America by European settlers rely heavily on plowing or tilling fields, which required making significant changes to the land by clearing vegetation, including clearcutting forests, to accommodate planting.

Traditional practices tied to a holistic approach to living in balance with the drivers of air, land, and watershed change are fundamental for Native American tribes in the United States, First Nations Aboriginal peoples in Canada, and Ejido communities in Mexico (Chief et al., 2016; NCAI 2015; Blackburn and Anderson 1993). These communities have ancestral ties to the land that span thousands of years. Many Indigenous communities are agrarian based, with their livelihoods and cultural

identity intimately associated with the health and well-being of the plants, fish, animals, and natural resources of their ancestral homelands (see Figure 7.1, p. 307). Livestock grazing and crop production; seed, nut, and plant gathering; and fishing and wildlife hunting are essential for cultural ceremonies, community wellness, and economic prosperity (AANDC 2013; Assies 2007; Chief et al., 2016; Tiller 1995, 2015).

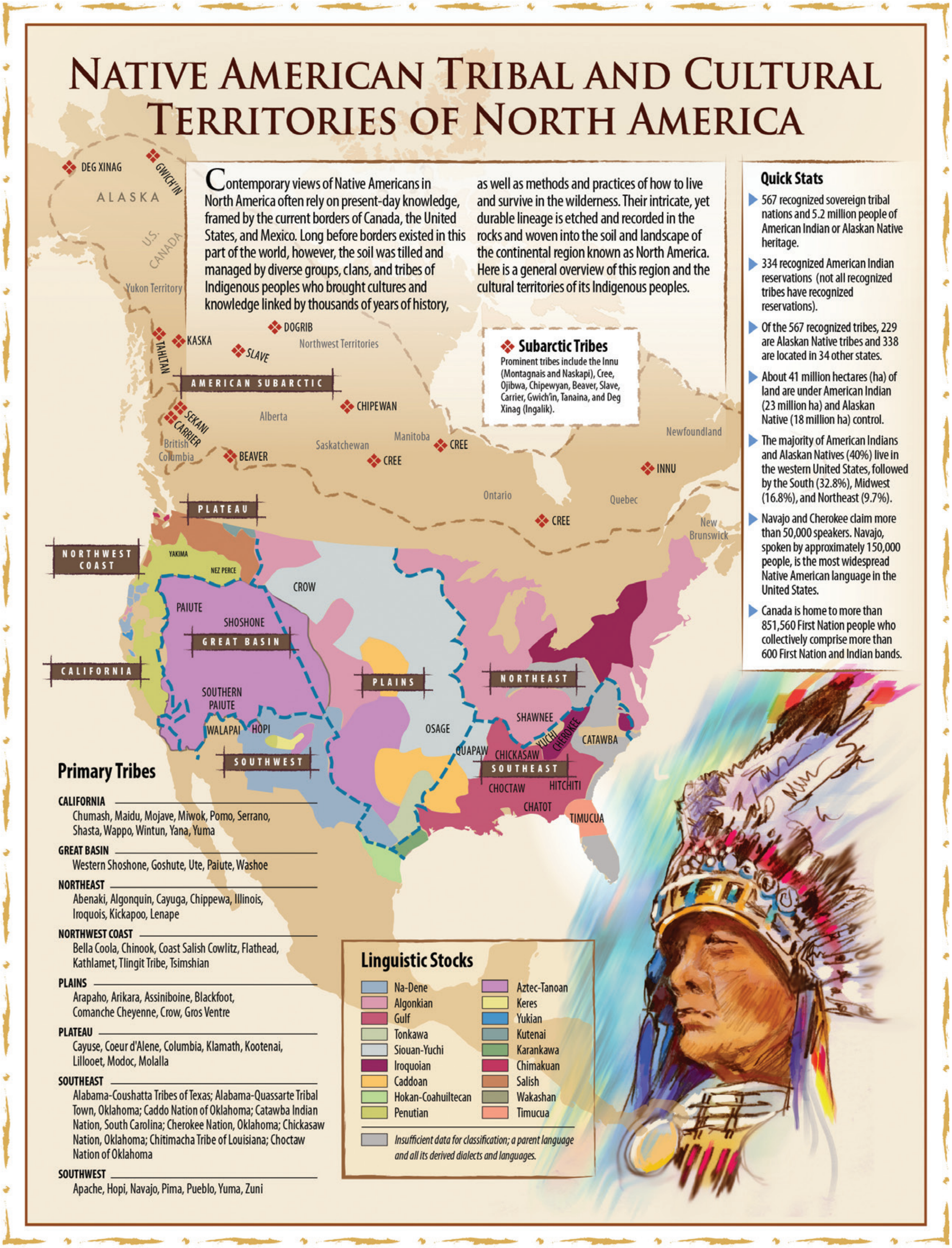
7.1.2 Carbon Cycling Considerations Unique to Tribal Lands

Carbon cycling among reservoirs in the atmosphere, terrestrial vegetation, soils, freshwater lakes and rivers, ocean areas, and geological sediments is integral to native landscapes. That said, discussions about how Indigenous peoples are affected by carbon cycle processes are different from similar discussions related to non-tribal lands, thus warranting separate consideration due to several key factors:

- Scientific data and peer-reviewed publications pertaining to carbon stocks and fluxes on reservation lands are virtually nonexistent, which makes establishing accurate baselines for carbon cycle processes problematic.
- Traditional knowledge about practices with bearing on carbon stocks on native lands (e.g., intergenerational stories, practices, and observations) often does not conform to mainstream science prescriptions for data gathered and analyzed for technical reports, including this report.
- Indigenous communities throughout North America are culturally distinct, with their own languages, practices, spiritual and cultural systems, governance structure, and deep connections to their lands, hence generalizations across North America may be of limited value.
- Native American communities in the United States and First Nations of Canada (but not Ejidos in Mexico) are recognized as sovereign nations with their own distinct policies, laws, and practices that may impact carbon stocks and fluxes on native lands.
- Native communities are heavily affected by the policies and laws of surrounding national, state, provincial, and local governments, as well as the economic and social drivers of non-tribal landowners and energy and natural resource extraction industries. Land-use decisions by native communities are influenced by high levels of poverty, unemployment, and health challenges.
- Complex Native American land tenure and water rights laws enacted by the U.S. and Canadian governments during the last two centuries have fractionated tribal land ownership, producing checkerboards of land types on reservations. In the United States, some of these lands are held “in trust” by the federal government, while others have been allotted or sold as “fee simple” lands that may be owned by one or many tribal or non-tribal individuals and subject to both tribal and non-tribal laws (Colby et al., 2005; McCool 2002; NCAI 2015; Pevar 2012; Thorson et al., 2006).

Opportunities for managing carbon stocks and fluxes present unique challenges to Indigenous peoples because of external stressors that constrain or complicate a community’s ability to sustain traditional practices that affect carbon processes. These include:

- The historical practice by the U.S. and Canadian governments of relocating Indigenous peoples from their expansive ancestral homelands to reservations on “marginal lands” in remote areas, which may or may not be contiguous with their sacred places. Similar disenfranchisement of Ejido communities has occurred in Mexico, where these isolated communities have little or no self-governance (OHCHR 2011; Pevar 2012; Russ 2013).
- Close cultural and economic ties to natural resources, geographic remoteness, and



NATIVE AMERICAN TRIBAL AND CULTURAL TERRITORIES OF NORTH AMERICA

Contemporary views of Native Americans in North America often rely on present-day knowledge, framed by the current borders of Canada, the United States, and Mexico. Long before borders existed in this part of the world, however, the soil was tilled and managed by diverse groups, clans, and tribes of Indigenous peoples who brought cultures and knowledge linked by thousands of years of history, as well as methods and practices of how to live and survive in the wilderness. Their intricate, yet durable lineage is etched and recorded in the rocks and woven into the soil and landscape of the continental region known as North America. Here is a general overview of this region and the cultural territories of its Indigenous peoples.

Quick Stats

- 567 recognized sovereign tribal nations and 5.2 million people of American Indian or Alaskan Native heritage.
- 334 recognized American Indian reservations (not all recognized tribes have recognized reservations).
- Of the 567 recognized tribes, 229 are Alaskan Native tribes and 338 are located in 34 other states.
- About 41 million hectares (ha) of land are under American Indian (23 million ha) and Alaskan Native (18 million ha) control.
- The majority of American Indians and Alaskan Natives (40%) live in the western United States, followed by the South (32.8%), Midwest (16.8%), and Northeast (9.7%).
- Navajo and Cherokee claim more than 50,000 speakers. Navajo, spoken by approximately 150,000 people, is the most widespread Native American language in the United States.
- Canada is home to more than 851,560 First Nation people who collectively comprise more than 600 First Nation and Indian bands.

❖ Subarctic Tribes

Prominent tribes include the Innu (Montagnais and Naskapi), Cree, Ojibwa, Chipewyan, Beaver, Slave, Carrier, Gwich'in, Tanaina, and Deg Xinag (Ingalik).

Primary Tribes

CALIFORNIA
Chumash, Maidu, Mojave, Miwok, Pomo, Serrano, Shasta, Wappo, Wintun, Yana, Yuma

GREAT BASIN
Western Shoshone, Goshute, Ute, Paiute, Washoe

NORTHEAST
Abenaki, Algonquin, Cayuga, Chippewa, Illinois, Iroquois, Kickapoo, Lenape

NORTHWEST COAST
Bella Coola, Chinook, Coast Salish Cowlitz, Flathead, Kathlamet, Tlingit Tribe, Tsimshian

PLAINS
Arapaho, Arikara, Assiniboine, Blackfoot, Comanche Cheyenne, Crow, Gros Ventre

PLATEAU
Cayuse, Coeur d'Alene, Columbia, Klamath, Kootenai, Lillooet, Modoc, Molalla

SOUTHEAST
Alabama-Coushatta Tribes of Texas; Alabama-Quassarte Tribal Town, Oklahoma; Caddo Nation of Oklahoma; Catawba Indian Nation, South Carolina; Cherokee Nation, Oklahoma; Chickasaw Nation, Oklahoma; Chitimacha Tribe of Louisiana; Choctaw Nation of Oklahoma

SOUTHWEST
Apache, Hopi, Navajo, Pima, Pueblo, Yuma, Zuni

Figure 7.1. Native American Tribal and Cultural Territories of North America. Overview of primary tribes, linguistic stocks, and extent of ancestral homelands. [Figure source: Ron Oden, University of Nevada, Reno. Data sources: NCAI 2015; Prine Pauls 2017; Sturtevant 1991; U.S. Census Briefs 2012; U.S. EIA 2017a.]

economic challenges make Indigenous peoples among the most vulnerable populations to climate change. These include (but are not limited to) tribes being displaced by rising sea levels and thawing tundra and those subjected to increased heatwaves, droughts, and extreme weather events that disrupt the traditional seasonal cycle and affect native fish, plant, animal, and water resources (Bennet et al., 2014; Melillo et al., 2014; Redsteer et al., 2018; Krakoff and Lavallee 2013).

- Colonial practices of relocation, termination, assimilation, and coercive exploitation of native lands have divided Indigenous communities and limited their ability to influence surrounding national and regional government decision making related to land use and carbon cycling (Anderson and Parker 2008; Bronin 2012).
- European settlement mandated that native communities convert traditional agriculture practices to Eurocentric crop and livestock production, which forced changes in landscapes, water supplies, and community health (Reo and Parker 2013; Kimmerer 2003; Thorson et al., 2006).
- Daunting socioeconomic challenges, including high levels of poverty and disease, demand significant time, attention, and resources and can influence land-use decision making by individuals and tribal governments. Native communities are heavily reliant on a wage economy and are subject to different federal policies than other citizens in their respective countries. The poverty rate for Native Americans living on reservations in the United States is 39% (the highest in the country), the joblessness rate is 49%, and the unemployment rate is 19%. Native health, education, and income statistics are likewise lower than those for any other racial group in the United States (NCAI 2015, 2016; GAO 2015; Indigenous Environmental Network 2016; Mills 2016; Regan 2016; Royster 2012; Notzke 1994; Assies 2007; Frantz 1999).

7.2 Historical Context and North American Perspective

Short summaries of Indigenous peoples of North America (United States, Canada, and Mexico) that are relevant to this report are provided in this section. See Appendix 7A: Summary Descriptions of Indigenous Communities in North America, p. 331, for additional details and references.

7.2.1 Governance and Population

Today, federally recognized Native American tribes operate under a government-to-government relationship with the U.S. government. First Nation tribes have similar self-government status within Canada. Mexico has no established system of reservations or formal system of Indigenous community self-government.

According to the 2010 Census, the United States is home to 5.2 million people of American Indian or Alaskan Native heritage. Together, they comprise the 567 federally recognized tribes in 35 U.S. States, 229 of which are in Alaska and the remaining 338 in 34 other states (NCAI 2015; U.S. Census Briefs 2012). About 41 million hectares (ha) are under American Indian or Alaskan Native control, with approximately 5.2 million people identified as American Indian/Alaskan Native (alone or in combination with other races). Approximately 22% of Native Americans live on tribal lands and 78% live in urban or suburban environments, with 19.5% of Native people living in Alaska (Norris et al., 2012).

According to the 2011 National Household Survey, Canada is home to 851,560 First Nation people that collectively comprise more than 600 First Nation and Indian bands. First Nation people make up about one-third of the total population in the Northwest Territories and one-fifth of the population in the Yukon (Statistics Canada 2011). Nearly half of those registered under Canada's Indian Act (49.3% or 316,000) live on reserves or Indian settlements (Statistics Canada 2011).

Indigenous communities in Mexico number 16.9 million people, the largest such community in North

America. Although Mexico does not have a system of reserves or reservations for Indigenous people, the majority (80%) of all people who speak an Indigenous language live in the southern and south-central regions of Mexico (Cultural Survival 1999; Minority Rights Group International 2017).

7.2.2 Land Use: Agriculture and Energy Extraction and Production

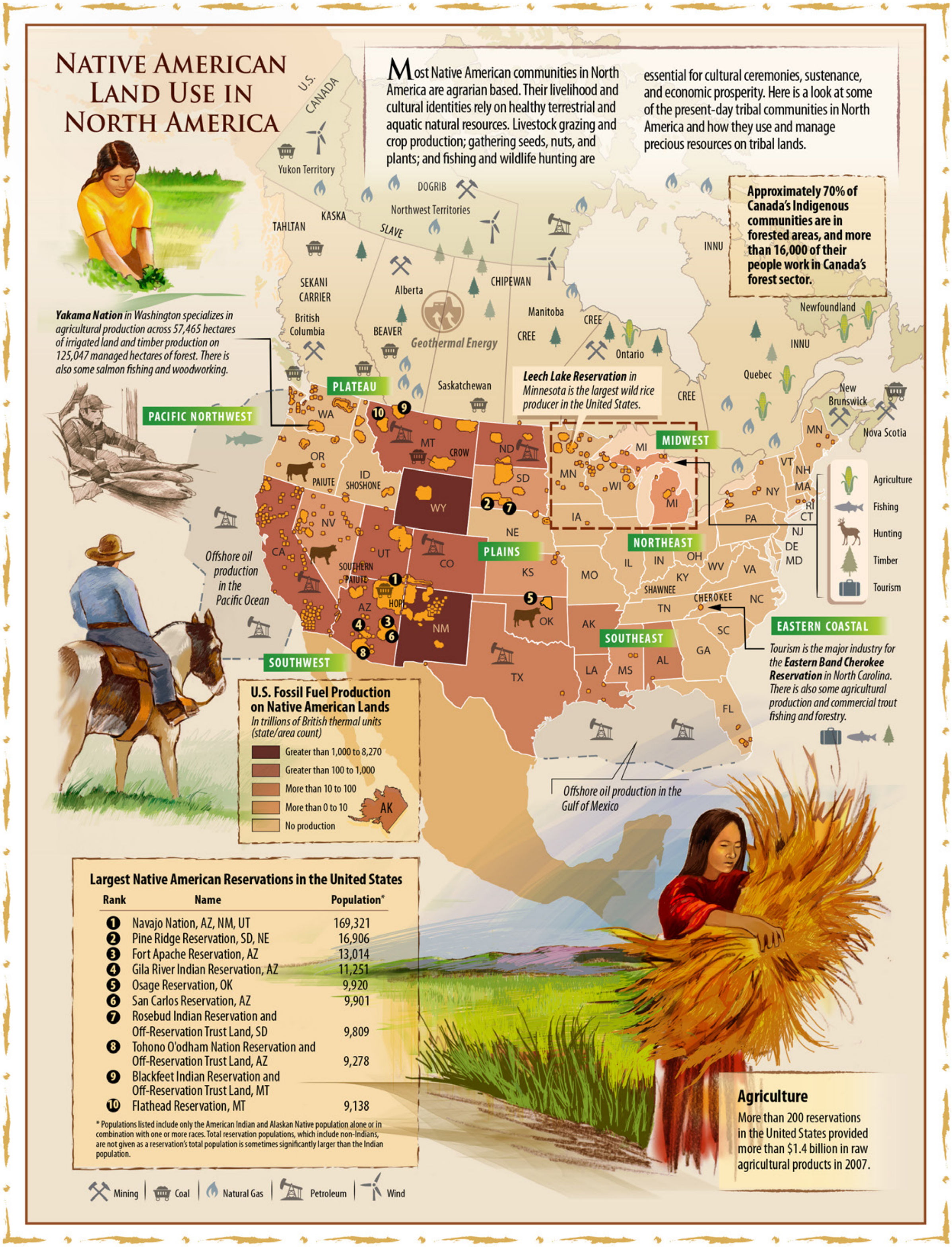
United States

Agriculture is an important industry for Native Americans across the United States, providing more than $1.8 billion in raw agricultural products in 2012 from 20.6 million ha of farmland ($700 million from crop sales and $1.1 billion from livestock; USDA 2014). About 80% of tribal agriculture occurs in seven states: Arizona, Oklahoma, New Mexico, Texas, Montana, California, and South Dakota (USDA 2014). Coal, natural gas, and oil reserves present opportunities for an estimated $1 trillion in revenue from mining and energy production across U.S. tribal lands (NCAI 2016), and commercial fisheries, forestry, tourism, energy extraction and generation, and other industries offer other opportunities for economic growth (see Figure 7.2, p. 310). Tribal lands emit a significant amount of carbon today, largely due to a history of federal policies of fossil fuel resource development on Native American reservations. Coal strip mining on Hopi, Navajo, and Crow tribal lands supply coal-fired power plants on and near these reservations, contributing to U.S. carbon emissions (U.S. EIA 2015; Krol 2018).

The National Indian Carbon Coalition (NICC) is one organization explicitly dedicated to engaging Native American communities in carbon management (NICC 2015). NICC is a greenhouse gas (GHG) management service established to encourage Native American community participation in carbon cycle programs with the goal of furthering both land stewardship and economic development on Native American lands. NICC was created as a partnership between the Indian Land Tenure Foundation and the Intertribal Agriculture Council to assist tribes in developing carbon credit programs. With waning U.S. interest in adopting a carbon credit economy, NICC may be less impactful than originally envisioned. However, NICC-sponsored programs represent focused efforts on carbon sequestration; GHG emission reductions; and the promotion of soil health, ecological diversity, and water and air quality in the context of traditional values and economic development. If the United States chooses to pursue a carbon credit economy in the future, programs such as NICC will be invaluable in positioning Native American communities to participate and benefit socially, culturally, and economically.

Land tenure; federal regulations, policies, and laws; and cultural values have made the extraction of fossil energy, uranium, and other mineral resources on tribal lands a socially and economically complex issue. The history of natural resource development on reservation lands, as well as policies such as the Indian Mineral Leasing Act, have led to a dependence on nonrenewable resources and narrowed the economic focus for revenues supporting many tribal governments (Krakoff and Lavallee 2013). As mentioned, Native American communities are among the nation's poorest, with nearly 40% of people on reservations living in poverty (four times the national average) and average annual incomes less than half those of other U.S. citizens (Grogan 2011). Such socioeconomic challenges have been attributed with motivating some tribes to allow extraction of their mineral and fossil fuel resources (Regan 2014). The U.S. Energy Information Administration (EIA) documents the energy profiles for each U.S. state and territory and updates them monthly, including descriptions of energy extraction and use on tribal lands (U.S. EIA 2017a).

Fossil fuel and uranium energy resources beneath tribal lands are substantial, comprising 30% of the nation's coal reserves west of the Mississippi River, 50% of its potential uranium reserves, and 20% of its known oil and gas reserves, together worth nearly $1.5 trillion (Grogan 2011). Most of these resources are concentrated with a few tribes in the western United States (Grogan 2011; Regan 2014;



NATIVE AMERICAN LAND USE IN NORTH AMERICA

Most Native American communities in North America are agrarian based. Their livelihood and cultural identities rely on healthy terrestrial and aquatic natural resources. Livestock grazing and crop production; gathering seeds, nuts, and plants; and fishing and wildlife hunting are essential for cultural ceremonies, sustenance, and economic prosperity. Here is a look at some of the present-day tribal communities in North America and how they use and manage precious resources on tribal lands.

Approximately 70% of Canada's Indigenous communities are in forested areas, and more than 16,000 of their people work in Canada's forest sector.

Yakama Nation *in Washington specializes in agricultural production across 57,465 hectares of irrigated land and timber production on 125,047 managed hectares of forest. There is also some salmon fishing and woodworking.*

Leech Lake Reservation *in Minnesota is the largest wild rice producer in the United States.*

Tourism is the major industry for the ***Eastern Band Cherokee Reservation*** *in North Carolina. There is also some agricultural production and commercial trout fishing and forestry.*

Offshore oil production in the Pacific Ocean

Offshore oil production in the Gulf of Mexico

Agriculture

More than 200 reservations in the United States provided more than $1.4 billion in raw agricultural products in 2007.

U.S. Fossil Fuel Production on Native American Lands

In trillions of British thermal units (state/area count)

- Greater than 1,000 to 8,270
- Greater than 100 to 1,000
- More than 10 to 100
- More than 0 to 10
- No production

Largest Native American Reservations in the United States

Rank	Name	Population*
❶	Navajo Nation, AZ, NM, UT	169,321
❷	Pine Ridge Reservation, SD, NE	16,906
❸	Fort Apache Reservation, AZ	13,014
❹	Gila River Indian Reservation, AZ	11,251
❺	Osage Reservation, OK	9,920
❻	San Carlos Reservation, AZ	9,901
❼	Rosebud Indian Reservation and Off-Reservation Trust Land, SD	9,809
❽	Tohono O'odham Nation Reservation and Off-Reservation Trust Land, AZ	9,278
❾	Blackfeet Indian Reservation and Off-Reservation Trust Land, MT	
❿	Flathead Reservation, MT	9,138

* Populations listed include only the American Indian and Alaskan Native population alone or in combination with one or more races. Total reservation populations, which include non-Indians, are not given as a reservation's total population is sometimes significantly larger than the Indian population.

Figure 7.2. Native American Land Use in North America. The size, scale, and location of some Native American reservations in the conterminous United States are shown, along with tribal fossil fuel production, population statistics, dominant industries by region, major socioeconomic drivers, and traditional practices (e.g., agriculture, hunting, and fishing). Coal strip mining on Hopi, Navajo, and Crow tribal lands supply coal-fired power plants on and near these reservations, contributing to U.S. carbon emissions. [Figure source: Ron Oden, University of Nevada, Reno. Data sources: NCAI 2015; Prine Pauls 2017; Sturtevant 1991; U.S. Census Briefs 2012; U.S. EIA 2017a; Natural Resources Canada 2016a.]

Table 7.1. Energy Resources on Tribal Lands in the United States[a]

Tribe	Fossil Fuel and Uranium Resources
Hopi (Arizona)	Coal, oil, and gas
Navajo (Arizona and New Mexico)	Coal, oil, gas, and uranium
Southern Ute (Colorado)	Coal, oil, and gas
Ute Mountain (Colorado)	Coal, oil, gas, and uranium
Blackfeet (Montana)	Coal, oil, and gas
Crow (Montana)	Coal, oil, and gas
Assinboine and Sioux (Montana)	Coal, oil, and gas
Northern Cheyenne (Montana)	Coal and oil
Jicarilla Apache (New Mexico)	Coal, oil, and gas
Three Affiliated Tribes (Fort Berthold, North Dakota)	Coal, oil, and gas
Osage (Oklahoma)	Oil and gas
Uintah and Ouray Ute (Utah)	Coal, oil, gas, and oil shale
Arapaho and Shoshone of Wind River (Wyoming)	Coal, oil, gas, and uranium

Notes

a) Regan 2014

see Table 7.1, this page; see also Ch. 3: Energy Systems, p. 110, for information about non-tribal energy extraction). Conflicts between traditional values and the need for economic development are demonstrated by uranium extraction on Navajo lands, where nearly 30 million tons were removed from over 1,000 mines from 1944 to 1986. Half of these mines are abandoned and awaiting remediation (U.S. EIA 2017b; U.S. EPA 2018; Moore-Nall 2015). Uranium mining provided some short-term benefits from mining income and jobs but resulted in extreme ecological degradation and long-term impacts to water, public health, and soil carbon sequestration (Brugge and Goble 2002; Diep 2010).

Recent discussions have emerged regarding strategies and policy tools that tribal governments could adopt in transitioning to carbon-neutral development and climate action plans (Suagee 2012). These strategies include updating substandard tribal housing and building new homes for the unmet housing need by addressing the lack of inclusion of federally recognized tribes in the U.S. Energy Independence and Security Act of 2007 (Public Law 110–140). Although this law requires housing to conform to an Energy Conservation Code, its application to tribal housing is generally lacking in order to limit the cost of such housing, leaving Native American home occupants with higher energy bills. The Indian Tribal Energy Development and Self-Determination Act provides additional frameworks for developing energy infrastructure (Anderson 2005), but the current legal framework does not adequately address tribal needs (Bronin 2012). The financial dependence of some tribes on fossil fuel extraction is a significant barrier to embracing carbon-neutral practices, especially when tribes are excluded from alternative energy tax credit incentives. For example, 85% of Hopi tribal revenues are from strip mining coal (Krol 2018). Moreover, rigorous studies on land-use impacts to ecosystems on tribal lands would help inform and motivate tribal governments to consider energy alternatives. Other challenges include environmental concerns, such as a lack of rigorous studies on land-use impacts to local ecosystems and the exclusion of tribes from incentives such as tax credits that are available to other entities developing alternative energy projects.

Canada

Indigenous communities in Canada rely heavily on sustenance and production agriculture (i.e., crops and livestock); fishing and hunting; forestry and timber harvesting; coal, oil, and gas extraction; and some alternative energy production (Canada Energy and Mines Ministers' Conference 2016; Merrill and Miro 1996; Natural Resources Canada 2016b). These activities, along with tourism, are the major economic drivers for tribal communities. Typically, Indigenous lands are sparsely populated with few (if any) commercial industries except those associated with gaming.

Forests and forest resources offer economic opportunities for the First Nations in Canada (Natural

Resources Canada 2016a). The Canadian government's Aboriginal Forestry Initiative provides information and support for Aboriginal forestry projects, as well as more than $10 million in funding opportunities across Canada for First Nations, which control more than 3,000 ha of forested land. Approximately 70% of Canada's Indigenous communities are in forested areas, and more than 16,000 Aboriginal people have worked in Canada's forest sector since 2011 for projects across the country (Natural Resources Canada 2016a).

Mining occurs on many First Nation lands, with over 480 mining agreements for more than 300 projects signed between mineral companies and Indigenous groups since 1974. As of December 2015, 380 projects were active (Canada Energy and Mines Ministers' Conference 2016). In the oil sands region of northern Alberta, some Indigenous communities are concerned about the environmental impacts of development, but the oil sands industry also provides economic opportunities for Indigenous-owned businesses that provide goods and services to oil sands companies (Natural Resources Canada 2016b). Fisheries are a traditional and modern source of livelihood for many Aboriginal people, especially in western Canada, where food fishing and commercial fishing are highly important (Notzke 1994).

Mexico

Temperate and tropical forests make up 56.8 million ha or 40.1% of Mexico's land area. Land reforms following the Mexican Revolution of the early 1900s put more than half the country's forested lands in the hands of "Ejidos" (communally owned farming collectives) and Indigenous communities (Bray et al., 2003). The result created community forest enterprises (CFEs), through which local communities own, manage, and harvest their own forest resources including timber. Although not all CFEs are well managed, they have the potential to provide income for poor, rural communities while delivering ecological services and maintaining forest productivity and biodiversity (Bray et al., 2003). The Mexican government initially owned Ejido lands, but a constitutional amendment in 1992 gave the farming collectives formal titles to their own lands (Merrill and Miro 1996).

7.3 Current Understanding of Carbon Stocks and Fluxes

Due to many of the factors previously cited, especially the lack of explicit measurements and data for carbon cycle processes, a quantitative assessment of the carbon stocks and fluxes for Indigenous lands does not presently exist. However, comparisons can be made about carbon cycling between tribal lands and similar, non-tribally managed land types (e.g., rangelands, agricultural lands, and forests). Comparing and contrasting carbon cycling impacts resulting from traditional practices on tribal lands with Eurocentric-based land-use practices on (and off) tribal lands could prove beneficial in developing more effective carbon management programs for both tribal and non-tribal lands. As in all systems, integrating scientific, social, and economic perspectives into strategies to use and protect natural resources and sustain healthy landscapes will be valuable to communities closely tied to the land.

Several case studies are presented throughout the rest of this section to illustrate 1) the role of Indigenous agricultural practices in maintaining or enhancing carbon sequestration on tribal lands, 2) the impacts of European settlement on traditional agriculture, 3) the role of Indigenous forest management approaches for sustaining forest health, and 4) the impact of fossil fuel and uranium extraction on tribal land carbon emissions, as well as the potential for renewable energy production.

7.3.1 Role of Indigenous Agricultural Practices in Maintaining or Enhancing Carbon Sequestration

Carbon can be stored above and below ground in vegetation (live or dead) and in soils on tribal lands such as agricultural lands, rangelands, aquacultural systems, and forests (Zomer et al., 2017; Baker et al., 2007). Compared to surrounding non-Indigenous lands, agricultural (crop and livestock) practices on

tribal lands tend to be significantly less intensive, with extensive reliance on free-range grazing, dryland farming, and no-till cropping especially in arid regions (Ingram 2015; Teasdale et al., 2007; Wall and Masayesva 2004; Kimmerer 2003). Because these traditional practices are less disruptive to native ecosystems, they tend to conserve carbon stocks on the landscape (Baker et al., 2007; West and Post 2002). However, compared to agriculture on non-tribal lands, traditional practices also may reduce economic output from crop production, cattle-carrying capacity on rangelands, and timber harvests (Drinkwater et al., 1998; Gabriel et al., 2006). Therefore, carbon inventories on native lands reflect a balance between sustaining traditional practices and the adoption of more intensive Eurocentric agricultural practices to increase trade and income.

The colonial-driven transformation of human and natural systems that pushed Native American communities to marginal areas and forced tribes onto restrictive reservations with limited options for food and safety (Lynn et al., 2013; Reo and Parker 2013), coupled with the introduction and adoption of Eurocentric agriculture, crops, and land-use practices, has (in many cases) led to desertification, soil degradation, erosion, and deforestation on tribal lands. These impacts, in turn, may have reduced the carbon-carrying capacity of the soils and vegetation (Redsteer et al., 2010; Baker et al., 2007; Kane 2015; Schahzenski 2009). Alfalfa, an introduced perennial crop with a deep root structure, is a dominant production crop and economic driver for many tribes in the arid southwestern United States (USDA 2014; U.S. Census Briefs 2012). Continuous alfalfa planting has been shown to contribute to the accumulation of soil organic carbon and total nitrogen under certain temperature and precipitation conditions (Chang et al., 2012). Overall, tribal and non-tribal carbon fluxes for multiple types of agriculture are probably close to net neutral in areas where both traditional and introduced agricultural practices are in use (see Ch. 5: Agriculture, p. 229). An exception is the continued use of slash-and-burn practices by some communities in Mexico (Bray et al., 2003; Deininger and Minten 1999).

Case Studies Utilizing Traditional Farming Practices for Carbon Sequestration

"For millennia, from Mexico to Montana, women have mounded up the earth and laid these three seeds (corn, beans, and squash) in the ground, all in the same square foot of soil. When the colonists on the Massachusetts shore first saw Indigenous gardens, they inferred that the savages did not know how to farm. To their minds, a garden meant straight rows of single species, not a three-dimensional sprawl of abundance. And yet they ate their fill and asked for more, and more again" (Kimmerer 2003).

Carbon sequestration projects on agricultural lands can be realized through improved management of fertilizer applications, erosion mitigation, return to no-till or reduced-tillage farming methods (depending on location), restoration of riparian areas, grazing management plans, good livestock waste management, and other measures (Zomer et al., 2017; West and Post 2002; Baker et al., 2007; see Ch. 5: Agriculture, p. 229, and Ch. 12: Soils, p. 469, for more information on no-till agricultural impacts on carbon sequestration). In southwestern Oklahoma, NICC worked with the Comanche Nation to establish a new agriculture leasing management system across 40,000 ha of allotments and tribal-owned land. Actions that could prove to be carbon sequestration measures on this reservation include a return to no-till farming, establishment of shelterbelts to prevent wind erosion, and rotational grazing management plans (NICC 2015).

On rangelands, overgrazing, soil erosion, wildfires, offroad driving, and conversion of rangeland to farmland can release carbon into the atmosphere, but carbon also can be sequestered through sustainable land management practices. On the Santa Ana Pueblo reservation in New Mexico, NICC worked with tribal members to improve land management for carbon sequestration across 4,000 ha. Provisions included increasing vegetation cover to prevent soil erosion, decreasing the density of woody species

to prevent wildfires, minimizing offroad driving, and developing and implementing livestock grazing plans (NICC 2015). On prairie lands, the Inter-Tribal Buffalo Council is a collaborative among 58 tribes in 19 states dedicated to restoring bison to Indigenous communities to promote Native American culture and spiritual practices, ecological restoration, and economic development. Bison have a smaller ecological impact on prairie lands than cattle, and their reintroduction by Indigenous communities in the Great Plains (albeit on a small scale compared to cattle ranching) is contributing to prairie restoration (Kohl et al., 2013).

There are data from across all of North America on traditional (Indigenous) agricultural practices going back several thousand years. Both oral tradition and written accounts dating from the 1500s show evidence of agricultural practices that are now being examined as a meaningful contribution to "carbon farming" or carbon sequestration via agricultural practices. These practices include no-till seeding, use of organic mulches (wood wastes and straw), use of composts (nonconsumed plant parts and animal wastes), moving domestic animals among areas based on season and forage availability, use of legumes (nitrogen-fixing plants), and complex cropping such as planting corn in perennial fields of clover or vetch (Baker et al., 2007; Drinkwater et al., 1998; Gabriel et al., 2006).

It has long been known that soil organic matter contains one of the planet's largest carbon sinks (see Ch. 12: Soils, p. 469; Zomer et al., 2017; Kane 2015; Marriott and Wander 2006; Teasdale et al., 2007). Various organizations, including Nourishing Systems in Oregon, are working to refine traditional methods of composting and soil carbon enrichment (Goode 2017). This approach, inspired by the Buffalo Dance tradition of the Northern Plains Tribes, is designed to mimic the soil nutrient cycling resulting from buffalo roaming on tallgrass prairie lands. Sunflower stalks, which are porous and recalcitrant (rich in lignin and therefore slowly degrading), are used as the base layer in the trenches between row crops and perennials (see Figure 7.3, p. 315). Less recalcitrant cellulosic wastes such as straw are placed on top of the sunflower stalks. As the final layers, wastes or the nonedible portions from crops are added as compost. These filled trenches are covered and used as walkways as the soils are enriched slowly by the decay of the organic matter, and the soil ecological assemblage of microorganisms, insects, and worms cycle the carbon and nutrients within the soil subecosystem (Goode 2017; Schahzenski and Hill 2009; West and Post 2002). A key to soil carbon sequestration may be a switch of the mechanisms that move soils away from bacterial dominance toward fungal dominance (Johnson 2017). At least in some systems, this change in soil community can result in increased soil fertility and water storage capacity, plant water-use efficiency, and soil nutrient availability to plants. The process also reduces plowing and tillage costs, fertilizer and pesticide applications, and water (both surface and groundwater) pollution (Johnson 2017).

"In Indigenous agriculture, the practice is to modify the plants to fit the land. As a result, there are many varieties of corn domesticated by our ancestors, all adapted to grow in many different places. Modern agriculture, with its big engines and fossil fuels, took the opposite approach: modify the land to fit the plants, which are frighteningly similar clones" (Kimmerer 2003).

The Pueblo Farming Project (Bocinsky and Varien 2017; Ermigiotti et al., 2018) has documented the drought resiliency of traditional Hopi farming practices, including the development of drought-tolerant Hopi corn varieties and dryland (non-irrigated) farming. An ongoing collaboration between the Hopi tribe and the Crow Canyon Archaeological Center in Cortez, Colorado, the Pueblo Farming Project has planted, tended, and harvested experimental gardens in southwestern Colorado every summer since 2008 to investigate the viability of growing Hopi maize outside of the Hopi mesas in northern Arizona. Traditional Hopi farmers grow their corn using entirely manual cultivation practices: a digging stick, a gourd of water, and seed corn selected to meet the subsistence and ritual needs of the Hopi community (Wall

Figure 7.3. Traditional Composting and Soil Carbon Enrichment. (a) Trenched complex compost for soil carbon accumulation in soil organic matter (SOM). **(b)** SOM development using trench composting. Key: H_2O, water; NH_4^+, ammonium; CO_2, carbon dioxide. [Figure source: Scott Goode, Desert Research Institute.]

and Masayesva 2004). With no tilling or tractors and minimal water inputs, Hopi corn farming maximizes moisture, nutrient, and carbon storage in the sandy soils of the Hopi mesas. As Hopi oral history attests and archaeologists have documented, traditional Hopi corn farming has sustained the Hopi community and their ancestors for millennia (Bocinsky and Varien 2017; Coltrain and Janetski 2013; Cooper et al., 2016; Matson 2016).

7.3.2 Impacts of European Settlement on Traditional Agriculture

For tribal communities that have adopted Eurocentric crop and livestock agricultural practices, carbon fluxes likely are comparable to fluxes from adjacent, non-tribal lands, including carbon losses due to soil erosion and desiccation. Before the 1860s, Navajo Nation families lived on a subsistence mix of farming, hunting and gathering, and herding livestock. This subsistence mix required families to range widely over a vast area of traditional Navajo lands (Fanale 1982). Families moved their livestock around core grazing areas shared by networks of interrelated, extended families; during droughts they used other kinship ties to gain access to more distant locations where conditions were better. This land-use regime helped families distribute their livestock over the range as conditions warranted (Redsteer et al., 2010). After the reservation was established in 1868, land-use pressure from non-Native American settlers cut them off from the wettest areas that were best for hunting, gathering, and summer grazing. Navajo families were forced to depend more heavily on farming and especially stock raising within the more arid to semi-arid sections of their homeland (Redsteer et al., 2010). By the early 20th century, both tribal and federal government officials along with other observers were warning about desertification of Navajo ranges (Kelley and Whiteley 1989; White 1983). Stock-reduction programs of the 1930s created further restrictions by establishing grazing districts and requiring each Navajo family to have a permit for raising livestock within a particular district, not to exceed a certain number (White 1983; Young 1961). Erosion has continued to be a problem, though range managers now recognize that climate, landscape conditions, and other hydrological processes also cause regional soil erosion even without additional grazing pressures (Redsteer et al., 2010; White 1983). Currently, the early 20th century grazing policies remain in place, and further revisions to grazing are being proposed as prolonged drought conditions from 1994 to 2018 and increasing aridity continue to degrade rangeland viability, water supplies, and general living conditions (Redsteer et al., 2018).

7.3.3 Role of Indigenous Forest Management Approaches for Sustaining Forest Health

Carbon fluxes between the biosphere and atmosphere may result in net carbon sinks (via carbon sequestration) in areas engaged in sustainable forest management and timber harvesting (see Ch. 9: Forests, p. 365). Numerous Indigenous communities throughout North America have sustainably managed forestlands, which may serve as carbon sinks in both tribal and non-tribal areas. Indigenous forestry practices in some cases have resulted in large and diverse stands of timber (Trosper 2007) that could be evaluated for their carbon storage impacts.

Case Studies of Sustainable Forest Management in the United States, Canada, and Mexico

United States. A renewed focus on traditional values, environmental stewardship, public health, and food sovereignty has led many Native American communities to adopt (or re-adopt) sustainable forest management practices rooted in their traditions and cultures. Exemplifying this renewed focus are the Confederated Salish and Kootenai Tribes (CSKT) of the Flathead Reservation in Montana, who have implemented an ecosystem-based forest management plan (Chaney 2013; CSKT 2000) that uses ecological, cultural, social, and economic principles to maintain and restore the ecological diversity and integrity of forests on the Flathead Reservation. Fire was integral to how the Salish, Kootenai, and Pend d'Oreille tribes managed the forests that provided them with sustenance and livelihood.

The CSKT have reintroduced traditional practices including the use of fire to manage their forests. These practices are enhancing forest ecosystem health and diversity and have reduced the impact of catastrophic wildfires that occurred on neighboring non-tribal federal lands (CSKT 2000). Carbon stocks are affected by the distribution and health of both trees and culturally important understory plants. Although fire can release large amounts of carbon and carbon stocks and fluxes have not been explicitly measured on the Flathead Reservation, the reintroduction of these traditional practices is resulting in more sustainable and healthy forests that are more diverse and fire-resistant.

Prior to European contact, the Salish, Kootenai, and Pend d'Oreille tribes of northwestern Montana (who were subsequently relocated to the Flathead Reservation) derived most of their sustenance from the surrounding forested lands, including culturally significant tree species (e.g., whitebark pine) and understory vegetation (e.g., huckleberries and medicinal plants; CSKT 2000). They used fire to actively manage forests for at least 7,000 years, according to oral tradition. These "Indian-lit fires" were usually set in the cooler days of spring, early summer, and fall when burning conditions were less hazardous; the fires were typically lower in intensity than lightening fires, which usually ignite in the hotter summer season. Using both fire and active harvesting, the tribes managed the forests holistically to balance stand density, understory vegetation health, and animal habitats to support hunting. The fire-exclusion policy introduced by the U.S. government in 1910, as well as the introduction of clearcut logging and cattle grazing, changed the biodiversity and health of these forests. During the last century, many tree stands have grown denser with many trees stressed from lack of water and insect and disease outbreaks. Although carbon stocks may have increased in these forests during this time, the forests are much more susceptible to catastrophic wildfires, as was evident in the summer of 2017 when over 405,000 ha were burned by wildfires in Montana (USDA 2017). Such burns, of course, result in large losses of carbon to the atmosphere.

Carbon sequestration projects involving forested land can also take the form of afforestation projects (i.e., planting trees on land that was previously unforested) or reforestation projects (i.e., planting trees in places where trees were removed). The Nez Perce Tribe of Idaho began an afforestation and reforestation project for carbon sequestration during the 1990s, planting trees on a 160-ha plot of previously unforested land. The tribe has since expanded its efforts to include 33 different afforestation and reforestation projects (including fire rehabilitation projects) covering approximately 1,379 ha (NICC 2015).

Canada. Canadian forest management programs include initiatives to build capacity and allocate revenues from resources shared among First Nations (AANDC 2012). With the emergence of carbon markets as an option for addressing climate change, First Nations formed the First Nations Carbon Collaborative, which is dedicated to building capacity among Indigenous communities to access and benefit from emerging carbon markets (IISD 2010, 2011). A goal of these programs is to address the economic challenges facing these communities by developing revenue-generating activities associated with carbon sequestration through sustainable forest management, restoration, and protection; biomass tree farming; and protection of boreal forest peatlands or "muskegs." The challenges identified by First Nations to engaging effectively in carbon markets are not unlike those faced by Indigenous communities in the United States and Mexico.

Mexico. Ejidos in Mexico are based on traditional Native American land-tenure systems that allow individuals to farm communally owned lands (Bray et al., 2003). An in-depth study analyzing the role of poverty, Ejido land tenure, and governmental policies in stimulating deforestation in Mexico revealed that poverty and government policies to hold maize prices above the world average increased deforestation (Deininger and Minten 1999). In contrast, Ejido communal land-tenure arrangements did not directly affect deforestation rates, and, within the Ejidos, Indigenous communities were associated with lower deforestation rates. Although several

factors likely contribute to this finding, evidence indicates that the sociocultural safety net provided by this traditional system of land use promotes natural resource management practices that overcome the "tragedy of the commons," which leads to land deforestation to increase cash crop production. In recognition of the benefits of dramatically reducing deforestation in Mexico and other developing countries, the World Bank and United Nations initiated two projects: the Forests and Climate Change Project (World Bank 2018) and REDD+, or the Reducing Emissions from Deforestation and Forest Degradation project (United Nations 2016). In May 2016, the World Bank reported that through job creation and other support to Ejidos and Indigenous communities, these programs have led to the conversion of 1.8 million ha of forestland to sustainable management, thus reducing Mexico's deforestation rates (World Bank 2018; United Nations 2016).

7.3.4 Impact of Energy Extraction and Production on Tribal Land Carbon Emissions

Within tribal lands, net carbon fluxes are estimated to be positive, with more carbon released to the atmosphere than is taken up in areas dominated by land leased for coal, oil, and gas extraction (primarily in the northern central United States and Canada). This is due to the carbon dioxide and methane (CH_4) released during extraction processes and the accompanying tree removal on forested lands. Fossil fuel extraction and uranium mining on tribal lands (described in the subsequent case studies) have resulted in significant ecosystem degradation and carbon emissions (Brugge et al., 2006). For tribal lands heavily vested in fossil fuel exploitation and use, carbon fluxes to the atmosphere may equal or even exceed those on similar non-tribal lands. Renewable energy generation on tribal lands primarily results from leasing lands or community-owned hydroelectric, geothermal, solar, wind, and biomass production facilities (U.S. DOE 2015).

Case Studies in Fossil Fuel and Uranium Extraction

The United States is a significant carbon emitter, and many of its fossil fuel resources are on tribal lands, where energy development is big business (Indigenous Environmental Network 2016; Mills 2016; Regan 2016). Fossil fuel and uranium extraction have provided economic gain for some tribes, but at the cost of significant environmental degradation, loss of cultural resources, and adverse health effects (Brugge 2006). Most of the low-sulfur coal mined in the United States is on tribal lands in the Southwest and Great Plains (Pendley and Kolstad 1980; NCAI 2015; U.S. EIA 2017a). The Osage tribe in Oklahoma and Crow Nation in Montana are pursuing coalbed CH_4 projects, while the Three Affiliated Tribes of the Fort Berthold reservation in North Dakota are entering the oil refinery business. The Southern Ute and Ute Mountain tribes in Colorado have developed their own oil business exploration and development companies and also have embraced coalbed CH_4 development. The Fort Mojave tribe along the lower Colorado River in Arizona and California is leasing its land to a California-based energy company, Calpine Corporation, to build a natural gas electrical generating plant. Easements allowing the building of electrical transmission lines throughout Indigenous lands are being negotiated, often without adequate input from grassroots tribal members.

Although nuclear energy production is carbon neutral, the human cost of nuclear fuels extraction has been high. The legacy of uranium mining and milling has resulted in considerable environmental and human health issues in Indigenous populations in the western United States, including the Navajo, Hopi, Southern Ute, Ute Mountain, Zuni, Laguna, Acoma, Eastern Shoshone, Northern Arapaho, and Spokane tribes. These legacy impacts are integral to the life cycle costs of nuclear energy production and should be included in assessments of nuclear energy's role in the carbon cycle. The largest open-pit uranium mine was located at Laguna Pueblo, New Mexico. Thousands of abandoned mining sites are

as yet unreclaimed, with 75% of unreclaimed mining sites occurring on tribal land (Moore-Nall 2015). Additional uranium milling locations are now "Superfund sites" (sites outlined in the U.S. Comprehensive Environmental Response, Compensation and Liability Act of 1980) on Navajo and Spokane tribal lands. Ecological destruction due to uranium mining and milling on tribal lands reduces the carbon-carrying capacity of these lands and impacts the ability of Indigenous communities to maintain traditional and sustainable land-use practices. The lack of compensation for human health impacts and continuing environmental problems resulting from uranium production led to the uranium mining ban on Navajo lands in the Diné Natural Resources Protection Act of 2005 (LaDuke 2005).

Case Studies in Renewable Energy Production

Renewable energy development on tribal lands is increasing (Jones 2014; Royster 2012) but is still limited by federal regulations, tribal land tenure, lack of energy transmission infrastructure on reservations, and economic challenges. Recent examples include a proposed solar facility on Hopi land near Flagstaff, Arizona, that would supply the town with electricity; two adjacent Navajo Nation solar projects near Kayenta, Arizona; and a Jemez Pueblo solar project in New Mexico (U.S. EIA 2017a). If these projects prove to be economically viable, increased interest and development of renewable energy resources on tribal lands may offset fossil fuel energy exploitation and consumption. One novel approach is the Tulalip Tribe's involvement in the Qualco anaerobic digester, which has been in operation since 2008. It utilizes animal waste, trap grease, and other pollutants (thus keeping them out of landfills and drains and preventing illegal dumping) and burns CH_4 to create renewable energy. This process helps clean the air and water, helps farmers keep their dairies operating, protects salmon streams, and provides environmentally friendly compost (Qualco Energy 2018).

7.4 Indicators, Trends, and Feedbacks

Ecological indicators, trends, and feedbacks for carbon cycle processes have not been monitored on tribal lands. As previously discussed, tribal communities that have adopted Eurocentric agricultural and land-use practices, such as raising cattle and growing irrigated crops, likely have land with carbon stocks and fluxes similar to those in neighboring non-tribal lands. In some cases, these stocks and fluxes could result in larger net carbon emissions to the atmosphere on tribal lands where reservation population pressures or adverse climatic conditions have increased land-use stresses. However, for other Indigenous lands, carbon stocks and fluxes may differ considerably from surrounding non-tribal areas because of more traditional and culturally distinct agricultural, forestry, and land-use practices. These practices include dryland farming, no-till seeding, in-ground soil composting, sustainable forest practices, and grazing management of open-range herds of bison and certain varieties of sheep.

Fossil fuel (e.g., oil, gas, and coal) extraction and uranium mining on tribal lands have produced significant ecological disturbances that affect carbon stocks and fluxes. Moreover, the carbon cycle impacts of fossil fuel extraction on tribal lands may exceed the impacts in non-tribal areas with active fossil energy economies when the accompanying ecological impacts are not addressed. In some cases, such as the abandoned uranium mines on Navajo Nation lands, the impacts of these disturbances were substantially greater compared to surrounding areas (Moore-Nall 2015).

Increased awareness of the value of Indigenous worldviews and traditional knowledge in sustaining landscapes that can effectively sequester carbon in soils and vegetation offers policymakers and resource managers insight into new approaches to carbon cycle management. Trends affecting carbon cycle processes in the future include 1) the cessation of uranium mining and decreases in fossil fuel extraction; 2) increasing on-reservation development and use of renewable energy; and

3) agricultural production adaptations increasingly based on traditional knowledge, which could include, but are not limited to, increasing reliance on traditional drought-resistant crops and agricultural practices and the local production of native foods.

7.5 Societal Drivers, Impacts, and Carbon Management

As previously described, carbon cycle issues are integral to natural resource and land management decision making by Indigenous communities across North America. Generational values rooted in deep connections to the Earth form the basis for many of these communities. Eurocentric agricultural practices and fossil fuel energy extraction challenge these values, especially when they promise opportunities for job creation and revenue generation for tribal communities facing extreme poverty, unemployment, and public health challenges. Inherent conflicts between traditional values and the need to improve community livelihoods underlie the societal drivers for land and natural resource management decisions that affect carbon management.

Current carbon cycle programs aiming to improve both land stewardship and economic development on tribal lands are constrained because of funding, education, governmental policies on agriculture pricing, and natural resource management, as well as limited federal government participation in global carbon markets. Indigenous communities share substantial socioeconomic challenges that make successful implementation of future carbon management programs dependent on revenue generation through sustainable management.

Drivers that can both positively and negatively affect carbon stocks and fluxes include:

- Increased population growth, increasing demand for water, and stresses from land use and limited natural resources in both tribal and surrounding non-tribal communities.
- Economic incentives for tribes to engage in fossil fuel extraction projects.
- Community stresses from high levels of poverty, unemployment, and public health issues.
- Strong cultural commitment to ecological stewardship among tribal members.
- Growing reliance on sustainable traditional agricultural and forestry practices and local native food production.
- Increased implementation of renewable energy projects on tribal lands for both local energy use and economic development.

7.6 Synthesis, Knowledge Gaps, and Outlook

As previously discussed, carbon inventories on native lands across North America are affected by the balance between the use of traditional practices and the economic drivers for more intensive agriculture and natural and energy resource exploitation. The extent to which traditional practices have been maintained or reintroduced serves as a guide for estimating carbon cycle impacts on tribal lands through comparisons to carbon cycle impacts on similar non-tribal land types.

Quantitative understanding of carbon stocks and fluxes on tribal lands is notably poor, with limited direct monitoring or modeling of carbon cycling. Nevertheless, carbon cycle issues are increasingly integral to natural resource and land management decision making, and they may be informed by further research involving partnerships to understand how traditional land-use practices alter the carbon cycle. Traditional Indigenous peoples' practices may offer new opportunities for carbon management. Further, because of the spatial extent of tribal lands and their potential to affect carbon cycling at large scales, an improved understanding of the carbon cycle on tribal lands would advance quantification of the continental carbon cycle. Many North American Indigenous communities maintain traditional practices that inherently affect carbon stocks and fluxes. These practices include sustainable management of forests, agriculture, and natural resources.

High levels of poverty and unemployment have encouraged some tribes with fossil fuel and mineral resources to engage in ecologically destructive extraction practices as a means to improve livelihoods. However, further development of renewable energy programs on tribal lands is providing new opportunities to improve reservation economies, community health, and carbon cycle sustainability.

7.6.1 Seven Generations Youth Education

Understanding the importance placed on youth education by Indigenous communities is critical to fostering and sustaining traditional practices of community and ecological sustainability that affect carbon management on tribal lands now and in the future. Tribal education is closely aligned with tribal core values and traditional concepts of sustainability and thus carbon cycle management (Tippeconnic III and Tippeconnic Fox 2012; Kimmerer 2002). In particular, youth are widely revered as representing the future vitality of tribal nations and tribal lands. This thinking is consistent with the core tribal value of sustainability, which often is articulated as planning for Seven Generations, that is, that the tribe's human, social, and natural capital must be sustained with a time horizon comparable to seven human life spans (Brookshire and Kaza 2013). Therefore, youth education, development, and leadership are near-universal tribal priorities, with tribal education being framed by traditional and cultural values and by deep connections to ancestral homelands (Cajete 1999). Tribal education is considered a journey and life pathway that is neither defined nor constrained by western notions of a segmented and stepwise educational pipeline. This approach has several practical implications. Tribal colleges and universities (TCUs) were created, in large part, to provide a culturally relevant educational pathway that is congruent with core tribal values, traditions, and commitments to sustainability (Benham and Stein 2003). TCUs often serve as the research and science centers for tribal nations, conducting primary research on tribal issues, maintaining repositories of cultural and natural assets, and facilitating long-term tribal planning on issues such as climate change and sustainability, economic development, and health and wellness. TCUs exemplify the Seven Generations approach by providing youth with the foundation, support, and pathway to become productive members of their tribal nation, thereby ensuring that the tribe and tribal lands will thrive into the future.

7.6.2 Knowledge Gaps and Ways Forward

Significant knowledge gaps remain in assessing the unique impacts of tribal land and resource management on carbon stocks and fluxes. Closing these gaps would benefit from the combined insight of native wisdom and western science about forest health, crop cultivation, livestock grazing, water management, ecosystem protection, and community health and well-being. These knowledge gaps should be discussed within the larger context and with a focus on ways to empower Indigenous communities and support their engagement in matters within their decision domains and spheres of influence that affect the carbon cycle. Research could usefully be directed at the unique circumstances and needs of Indigenous communities. Particular research needs include:

- Quantifying the impacts of traditional practices on carbon stocks and fluxes, including the use of fire on the landscape, co-cropping of synergistic plants, and cultivation of plants with high moisture retention and temperature tolerance.

- Evaluating potential changes in carbon fluxes from site-specific applications of carbon capture and sequestration efforts and developing quantification methods for projects involving soil enrichment and renewable energy.

- Evaluating opportunities for deploying innovative technologies and practices that potentially can affect carbon fluxes at the community level (e.g., renewable energy, energy-efficient substitutions, local sourcing, carbon-based purchasing policies, and carbon markets).

Actions that may contribute to future carbon storage and reduce carbon emissions on tribal lands include:

- Developing community-based programs that address carbon sequestration in the context of enhanced access to nutritional foods.
- Promoting intergovernmental coordination and cooperation among partners to preserve and protect the public trust, as well as the use of special relationships such as fiduciary obligations and consultation requirements and principles of free, prior, and informed consent (United Nations 2008).
- Advancing collaborative efforts to increase awareness and combine western science and traditional knowledge, including facilitation of access to and sharing of data, information, and expertise.
- Implementing place-based monitoring and systems for recording and reporting environmental observations to establish baselines and provide a history of changes in temperature, humidity, precipitation, phenology, and species compositions.
- Increasing knowledge sharing about traditional agricultural practices that minimize carbon emissions and enhance carbon storage.
- Engaging in outreach education about alternative, efficient, and economical energy production on tribal lands.
- Implementing programs that enable tribes to quantify and realize the economic benefits associated with sustainable forest management, reforestation, boreal forest protection, and sustainable agriculture.
- Building capacity among tribal youth to support and inform the next generation of decision makers.

Indigenous communities are continuing to create opportunities to locally develop more diverse, distributed, and sustainable sources of energy, food, and income, which is strengthening ecological and community resilience and enhancing sustainable carbon management.

SUPPORTING EVIDENCE

KEY FINDING 1

Many Indigenous peoples in North America follow traditional agricultural and land-use practices that govern carbon cycling on tribal lands. These practices include no-till farming; moving domesticated animals seasonally in accordance with forage availability; growing legumes and cover crops; raising crops and livestock native to ancestral landscapes; and managing forests sustainably with fire, harvest, and multispecies protection.

Description of evidence base

Key Finding 1 is supported by studies and detailed reports about Indigenous tribes (e.g., AANDC 2013; Assies 2007; Chief et al., 2016; NCAI 2015; Tiller 1995) and agricultural crop and grazing and forestry practices (Zomer et al., 2017; Baker et al., 2007; Redsteer et al., 2010; Drinkwater et al., 1998; Gabriel et al., 2006; CSKT 2000; Bennet et al., 2014).

Major uncertainties

Uncertainties result from the limited number of reports in the literature documenting the extent to which traditional practices on native lands have impacted carbon cycle processes.

KEY FINDING 2

Scientific data and peer-reviewed publications pertaining to carbon stocks and fluxes on Indigenous (native) lands in North America are virtually nonexistent, which makes establishing accurate baselines for carbon cycle processes problematic. The extent to which traditional practices have been maintained or reintroduced on native lands can serve as a guide for estimating carbon cycle impacts on tribal lands by comparisons with practices on similar non-tribal lands.

Description of evidence base

Key Finding 2 is supported by findings presented in the *First State of the Carbon Cycle Report* (CCSP 2007) and resources on carbon programs in the United States (NICC 2015), deforestation in Mexico (Deininger and Minten 1999), and the First Nations Carbon Collaborative in Canada (IISD 2010, 2011).

Major uncertainties

Uncertainties result from a lack of in-depth studies and technical reports documenting carbon stocks and fluxes on tribal lands throughout North America.

KEY FINDING 3

Fossil fuel and uranium energy resources beneath tribal lands in the United States and Canada are substantial, comprising, in the United States, 30% of coal reserves west of the Mississippi River, 50% of potential uranium reserves, and 20% of known oil and gas reserves, together worth nearly $1.5 trillion. Fossil fuel extraction and uranium mining on native lands have resulted in emissions of carbon dioxide and methane during extraction and fuel burning. Energy resource extraction on tribal lands also has resulted in substantial ecosystem degradation and deforestation, further contributing to carbon emissions.

Description of evidence base

Key Finding 3 is supported by resources on fossil fuel and uranium extraction on tribal lands (Indigenous Environmental Network 2016; Mills 2016; Regan 2014, 2016; U.S. EIA 2017a, 2017b; Grogan 2011; U.S. EPA 2018; Moore-Nall 2015) and on ecological degradation from energy extraction (Brugge and Goble 2002; Diep 2010).

Major uncertainties

Uncertainties result from the lack of carbon emissions monitoring during energy extraction on tribal lands. Although energy extraction and use on Native American and First Nation lands are fairly well documented, carbon emission and consumption measurements are scarce, and studies of the adverse effects of tribal fossil fuel economies are limited.

KEY FINDING 4

Renewable energy development on tribal lands is increasing but is limited by federal regulations, tribal land tenure, lack of energy transmission infrastructure on reservations, and economic challenges.

Description of evidence base

Key Finding 4 is supported by reports on the opportunities and challenges for renewable energy production on tribal lands in the United States (Saugee 2012; Anderson 2005; Bronin 2012; U.S EIA 2017a, 2017b; Jones 2014; Royster 2012; Canada Energy and Mines Ministers' Conference 2016; Natural Resources Canada 2016a; Notzke 1994].

Major uncertainties

Uncertainties result from a limited number of case studies of areas where renewable energy sources have been developed and operated on tribal lands for extended periods of time.

KEY FINDING 5

Colonial practices of relocation, termination, assimilation, and natural resource exploitation on native lands have historically hindered the ability of Indigenous communities to manage or influence land-use and carbon management both on and off tribal lands. These factors combined with contemporary socioeconomic challenges continue to impact Indigenous carbon management decision making.

Description of evidence base

Key Finding 5 is supported by reports on climate vulnerability of Indigenous peoples (Bennet et al., 2014; Melillo et al., 2014) and the impacts of European settlement on tribal communities (NCAI 2015; GAO 2015; Indigenous Environmental Network 2016; Mills 2016; Regan 2016; Royster 2012; Statistics Canada 2011; Cultural Survival 1999; Minority Rights Group International 2017).

Major uncertainties

Uncertainties result from the limited number and duration of carbon cycle education programs implemented in North America and globally.

KEY FINDING 6

The importance placed on youth education by Indigenous communities creates opportunities for future generations to sustain and pass on traditional knowledge important to managing carbon stocks and fluxes on native lands.

Description of evidence base

Key Finding 6 is supported by reports on the tribal community youth education programs in the United States (Tippeconnic III and Tippeconnic Fox 2012; Kimmerer 2002; Cajete 1999; Brookshire and Kaza 2013).

Major uncertainties

Uncertainties result from the limited number of comprehensive studies on the role youth education plays in sustaining traditional practices for different Indigenous groups in Mexico and Canada, as well as uncertainty in the magnitude to which those practices could affect the carbon cycle.

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Appendix 7A
Summary Descriptions of Indigenous Communities in North America

7A.1 Location and Populations

According to the 2010 Census, the United States is home to 5.2 million people of American Indian or Alaskan Native heritage. Together, they comprise the 567 federally recognized tribes, 229 of which are in Alaska and the remaining 338 in 34 other states (NCAI 2015; U.S. Census Briefs 2012). About 41 million hectares (ha) are under American Indian or Alaskan Native control, with approximately 5.2 million people identified as American Indian/Alaskan Native (alone or in combination with other races). Approximately 22% of Native Americans live on tribal lands and 78% live in urban or suburban environments, with 19.5% of Native people living in Alaska (Norris et al., 2012).

Most American Indians and Alaskan Natives live in the western United States (40.7%), followed by the South (32.8%), Midwest (16.8%), and Northeast (9.7%; Norris et al., 2012). States with the highest populations of Native Americans living on or near tribal reservations are Oklahoma (471,738), California (281,374), and Arizona (234,891; BIA 2013). The largest reservation in the United States is the Navajo Nation Reservation of Arizona, New Mexico, and Utah (about 7 million ha), with a population of 169,321. The second most populated reservation is Pine Ridge Reservation in South Dakota and Nebraska, with 16,906 Native Americans (Norris et al., 2012).

According to the 2011 National Household Survey, Canada is home to 851,560 First Nation people that collectively comprise more than 600 First Nation and Indian bands. Of these, most live in Ontario and the western provinces. For example, about 23.6% of Canada's First Nation people live in Ontario (201,100), 18.2% in British Columbia (155,020), and 13.7% in Alberta (116,670; Statistics Canada 2011). First Nation people make up about one-third of the total population in the Northwest Territories and one-fifth of the population in the Yukon. Of the 851,560 people who self-identify as First Nations, 637,660 are officially registered under Canada's Indian Act. Nearly half of those registered (49.3%, or 316,000) live on reserves or Indian settlements (Statistics Canada 2011).

Mexico's Indigenous community consists of 16.9 million people, the largest such community in North America. These people represent 15.1% of the national population and together speak 68 Indigenous languages and 364 dialects (Del Val et al., 2016). Although Mexico does not have a system of reserves or reservations for Indigenous people, the majority (80%) of all people who speak an Indigenous language live in the southern and south-central regions of Mexico (Cultural Survival 1999; Minority Rights Group International 2017). About 18.1% of Mexico's Indigenous people live in the state of Oaxaca, followed by Veracruz (13.5%), Chiapas (13%), Puebla (9.42%), Yucatán (8.2%), Hidalgo (5.7%), state of Mexico (5.6%), Guerrero (5.2%), San Luis Potosí (3.2%), and Michoacán (2.9%; (Cultural Survival 1999).

7A.2 Summary Descriptions by Geographical Region

7A.2.1 Native Americans in the United States

Alaskan Native

Alaska is home to only one federally designated reservation, and most Alaskan Natives are associated with village or regional "corporations" (created by the 1971 federal Alaska Native Claims Settlement Act). Many of the native communities

reside in coastal areas where commercial fishing and tourism are two major sources of income (Tiller 1995). Some of these communities face imminent relocation due to rising sea levels (Melillo et al., 2014).

Pacific Northwest

The Yakama Nation specializes in agricultural production across 57,500 ha of irrigated land and in forestry on 125,000 managed ha of timber. Fisheries along the Columbia River are primarily for subsistence and ceremonial use, and tourism supports other members of the tribe (Tiller 1995). Along the coast, the Quinault Indian Nation uses its reservation's resources primarily for fisheries, timber harvesting, and tourism related to trout and salmon fishing (Tiller 1995).

Southwest

The southwestern United States is home to some of the country's largest reservations, including the Navajo Nation (6,566,000 ha in Arizona, New Mexico, and Utah); Hopi (632,000 ha surrounded by the Navajo Nation in Arizona); and Tohono O'odham (1.1 million ha straddling the U.S.-Mexico border). Major industries and land uses on these reservations include mining of coal, oil, and natural gas and tourism in parks, monuments, and recreation areas (Tiller 1995). For other southwestern reservations, main industries and land uses are production agriculture and livestock (Gila River Indian Community in Arizona and Walker River Paiute Tribe in Nevada), fisheries (Pyramid Lake Paiute Tribe in Nevada), and mineral mining (Uintah and Ouray Reservation in Utah; Tiller 1995).

Intermountain West

The large Blackfeet, Flathead, and Crow reservations in Montana contain rich farmland; extensive livestock grazing areas; commercial timberland; and coal, oil, and natural gas resources that, along with tourism, support the local economies. Land leases for energy extraction, hydroelectric power generation, and timber harvesting provide significant revenue streams for the tribes (Tiller 1995).

Great Plains

Some of the largest reservations in this region are in the Dakotas (e.g., Standing Rock, Cheyenne River, and Pine Ridge), where major industries and sources of tribal income include agriculture, oil and natural gas mining, forestry, and tourism (Tiller 1995).

Midwest

Most tribal reservations in the Midwest are in Michigan, Wisconsin, and Minnesota where timber harvesting, agriculture, big game hunting, fisheries, and tourism are major industries. In Wisconsin, the economy of the Menominee Indian Tribe revolves around sustainable forestry practices, with 95% of tribal lands forested after more than 100 years in the forestry industry (Tiller 1995). The Leech Lake Band of Ojibwa in Minnesota is the largest wild rice producer in the United States, with 4,000 ha of wild rice fields (Tiller 1995).

East Coast

Tribal reservations in the eastern United States are generally much smaller than those in the West because of European settlement, assimilation, and forced relocation. The Cherokee are the largest tribe in the United States, and their ancestral territory spanned over eight southeastern states. Most of the Cherokee Nation was forced to relocate to Oklahoma under an 1835 treaty. The Eastern Band of the Cherokee, who resisted removal during the 1800s, maintain a reservation in western North Carolina where tourism is a major industry and some commercial revenues are produced from small-scale farms and ranches. Tribes in the Northeast, such as the Allegany Reservation in New York, rely on agriculture, livestock, and some commercial forestry (Tiller 1995).

7A.2.2 First Nations of Canada

Eastern Canada: Quebec, Ontario, Newfoundland, and Labrador

In Canada's eastern woodlands region, First Nation tribes traditionally consisted of small groups (fewer than 400 people) who migrated in search of food, subsisting via hunting and trapping of migratory

animals. In fertile regions of southeastern Canada, the Iroquoian First Nations founded permanent communities where they farmed food crops, including corn, beans, and squash (AANDC 2013). Today, forestry provides opportunities for Indigenous people. In Newfoundland, Labrador, Quebec, and the Yukon, modern treaties have resulted in the transfer of more than 6 million ha to First Nation people. In Ontario, a 2014 to 2015 forest tenure modernization project provided funding to support sustainable forest licenses for Indigenous communities (Natural Resources Canada 2016a).

Central Canada: Alberta, Saskatchewan, and Manitoba

On the plains, First Nation people traditionally lived as migratory groups of hunters who followed the buffalo herds (AANDC 2013). Today, geothermal energy produced on the Peguis First Nation and Fisher River Cree Nation Reserve in Manitoba heats reserve homes, and First Nation people are trained and certified in geothermal trades (Paul 2015). On the remote Opaskwayak Cree First Nation reserve, where fresh produce is expensive, community members are experimenting with a method for indoor farming called "vertical farming" (CTV News 2016).

Western Canada: British Columbia

Along the Pacific Coast, First Nation people traditionally settled in permanent villages and subsisted on food resources from the ocean such as salmon, shellfish, sea lions, otters, whales, and seaweed. Red cedar from forests along the coast was used to build homes (AANDC 2013). Today, fisheries are an important industry for First Nations located in western Canada, where salmon, halibut, herring, and other fish are caught and processed in canneries (Notzke 1994). Forestry is also an important industry in this region. The First Nations Forestry Council of British Columbia works to support First Nation forestry activities through training programs, business support, policy development, mountain pine beetle action plans, ecosystem stewardship planning, and more (B.C. First Nations Forestry Council 2015). In central British Columbia, a liquid natural gas pipeline called Pacific Northwest LNG is under development. For environmental reasons, some First Nation groups oppose the pipeline while others support it for the economic benefits it will bring their First Nation communities (Jang 2016).

The Far North: Yukon and Northwest Territories

First Nation people of northwestern Canada traditionally hunted for game animals such as caribou across large territories (AANDC 2013). Today, the Yukon and Northwest territories are used for renewable and nonrenewable energy projects such as crude oil, natural gas, thermal electrical facilities, hydroelectric plants, and wind energy projects. Several pipelines carry crude oil and natural gas through the region (Canada National Energy Board 2011). Some First Nation people oppose energy development projects. For example, in the Yukon Territory, members of the Vuntut Gwitchin First Nation live along the migration route of the Porcupine caribou herd and rely on resources provided by the herd for food, clothing, and crafts. Their traditional way of life is being threatened by oil and gas companies that want to develop the Arctic National Wildlife Refuge (Vuntut Gwitchin First Nation, N.D.).

7A.2.3 Indigenous Communities in Mexico

Oaxaca and Guerrero

In the La Mixteca region of Mexico, which covers portions of the states of Oaxaca, Puebla, and Guerrero, centuries of destructive land-use practices have converted forest into desert. Here, Mixteca Indian farmers are reviving pre-Hispanic farming practices to restore and farm the land. Actions taken by these farmers include terracing hillsides, plowing with oxen, and farming via a technique called "milpa," where corn, squash, and beans grow together and increase soil nutrients (Malkin 2008).

Yucatán Peninsula and Quintana Roo

In Quintana Roo, forest resources provide a major source of income for the Mayan people, who make up about 25% of the population (Bray et al., 1993). Traditionally, the Maya used the forest for nontimber products such as palms for roof thatching,

fruits and herbs for food and medicine, and deer and peccary for meat. In the 1970s, the Maya and members of local Ejidos (communally farmed lands) began to harvest trees for railroad ties. In the 1980s, a forestry pilot program helped members of the Ejidos learn timber marketing strategies and sustainable management techniques. The Ejidos of central Quintana Roo occupy more than 400,000 ha of forest, much of which is permanent forest reserve (Bray et al., 1993).

Sierra Madre Occidental (Jalisco, Nayarit, Zacatecas, and Durango)

In the Sierra Madre Occidental Mountains, Huichol people live as subsistence farmers, using slash-and-burn practices to convert forest into agricultural land. They produce mostly maize, but also beans, squash, and sometimes livestock. Some Huichol are cattle ranchers, and others sell lumber. The quality of Huichol land is harmed by the slash-and-burn farming, and cattle grazing further damaged soil quality (Cultural Survival 1992).

Central Highlands, Sierra Norte de Puebla, and the Gulf Coast

The Nahua, speakers of the Nahuatl language, live near what was once the center of the Aztec empire. Most Nahua farm, growing maize, beans, chili peppers, squash, camotes, onions, tomatoes, and other cash crops such as sugarcane and coffee. Most families supplement farming with other sources of income (Sandstrom 2008).

7A.3 Land Tenure and Water Rights

U.S. reservation lands not "allotted" to individual tribal members under laws enacted in the late 1800s and early 1900s are held "in trust" by the U.S. government, meaning that the federal government must manage the lands and resources in a manner most beneficial to tribes (NCAI 2016). While tribal governments have the authority to manage their land base, the complexities of overlapping jurisdictions and land-use customs can delay crucial resource management decisions. For this reason, tribally owned lands may face greater obstacles to achieving sustainable resource management than public or private lands (Anderson and Parker 2008; Russ and Stratman 2013).

Land-tenure issues create challenges for tribal communities managing natural resources on reservation lands. Some reservations consist entirely of trust land, but, as a result of the General Allotment Act of 1887, many reservations also include other types of land, such as land owned by individual Indian families or land owned by non-Indigenous people who acquired the land from tribal families (Frantz 1999). The resulting checkerboard pattern of land ownership on many reservations is problematic for farming, ranching, and other activities—including developing and implementing carbon management plans—that require access to or management of large land tracts (Indian Land Tenure Foundation 2016). On trust lands, approval by the U.S. Secretary of the Interior is required for most land-use decisions, complicating tribes' ability, for example, to sell, lease, or develop their lands (Indian Land Tenure Foundation 2016).

In addition to land-tenure issues, Native American tribes in the United States have historically faced challenges in obtaining water for their reservations (Colby et al., 2005; McCool 2002; Thorson et al., 2006). In arid regions of the West, early settlers began a tradition of removing water from rivers via dams, diversions, and canals for agriculture, mining, and other purposes. Native American reservations downstream from western civilizations had no guarantee of sufficient water delivery during much of the 1800s. A 1908 Supreme Court decision known as the Winters Doctrine set the priority use date for water rights on tribal reservations as the same date that each reservation was established regardless of whether the tribe was using water for irrigation or other purposes at that time (Frantz 1999). The Winters Doctrine means that, today, tribes hold some of the most senior (highest-priority) water rights (referred to as "paper water") on river systems in the West. However, gaining access to actual water allocations ("wet water") can still be a long and arduous process for tribes that involves legal settlements

or adjudication agreements with federal and state governments.

On Canadian First Nation reserves, land is held in trust by the crown for use by specific bands. A "First Nation band" (or First Nation) is a recognized self-governing Indigenous community under the Indian Act of 1876 (Canada Indian Act 1985). The Canadian government may assign individual Indians the right to use land via certificates of possession (CP), but they do not have full legal ownership. Land not assigned by CP to an individual is held as community property of the band. Although bands may not sell reserve land, they may lease it to non-Indigenous people for uses such as natural resource development, farming, ranching, recreation, or rights-of-way for transportation or transmission (McCue 2011). Canadian First Nation tribes face land-tenure challenges similar to those confronting many Native Americans in the United States. Land-use opportunities may be limited by a reserve's location (e.g., areas with limited economic opportunities) or resource scarcity. Governmental regulations on access to fish, timber, mineral, subsurface, and other resources may restrict band members' efforts to develop land. In addition, reserve lands often are intersected by government rights-of-way for power lines, railroads, and highways, dividing useable spaces and making land use more difficult (Hanson 2009).

Water rights laws differ by province across Canada and consist of either prior allocation, public authority, riparian rights, or civil code. In addition, Indigenous and Canadian water rights laws co-exist. Prior to colonization, Indigenous cultures governed water use via their own customs and practices. The Constitution Act of 1982 protects any Indigenous rights (including water) not taken away from First Nations by 1982 (Canada Program on Water Governance 2010).

Unlike the United States and Canada, Mexico does not have a system of federal reserves or reservations. Rather than setting aside land and resources for Indigenous people, the Mexican government historically focused on cultural integration via assimilation (Minority Rights Group International 2017). Today, Mexico's constitution guarantees Indigenous people the right to self-determination, including the right to autonomy, education, infrastructure, and freedom from discrimination (Aban 2015). Each state has its own constitution, and some states have established legislation that limits the rights recognized by the national constitution (OHCHR 2011). Rights of Indigenous people vary from state to state; in Chiapas, Michoacán, and Oaxaca, Indigenous people have formed autonomous Indigenous governments (Minority Rights Group International 2017).