Preface

About This Report

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

Intended Audience

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

USGCRP's Sustained Assessment Process and the National Climate Assessment

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

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

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

Box P.1 Carbon Cycle Terminology and Reporting Units

Sources, Sinks, and Transfers

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

Reporting Units

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

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

report, SOCCR2 provides a comprehensive assessment of the science and associated human dimensions of carbon cycling in land, air, and water, with a focus on the United States and North America in a global context. SOCCR2 contributes to and informs the congressionally mandated National Climate Assessment (NCA) process of the Global Change Research Act (1990). The report also updates the carbon cycle science presented in the *Third National Climate Assessment* (NCA3; Melillo et al., 2014) and provides the authors of the forthcoming NCA4 Vol. II with additional consensus-based carbon cycle knowledge to bolster their own assessment of the impacts and risks posed by climate change across regions and sectors of the United States. The USGCRP assessment reports together cover sectors and topics (see Table P.1, p. 8) mandated by the Global Change Research Act (1990), responding to Section 106 on Scientific Assessments by:

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

Sources Used in This Report

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

Report Development, Review, and Approval Process

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

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

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

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

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

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

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

Notes

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

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

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

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

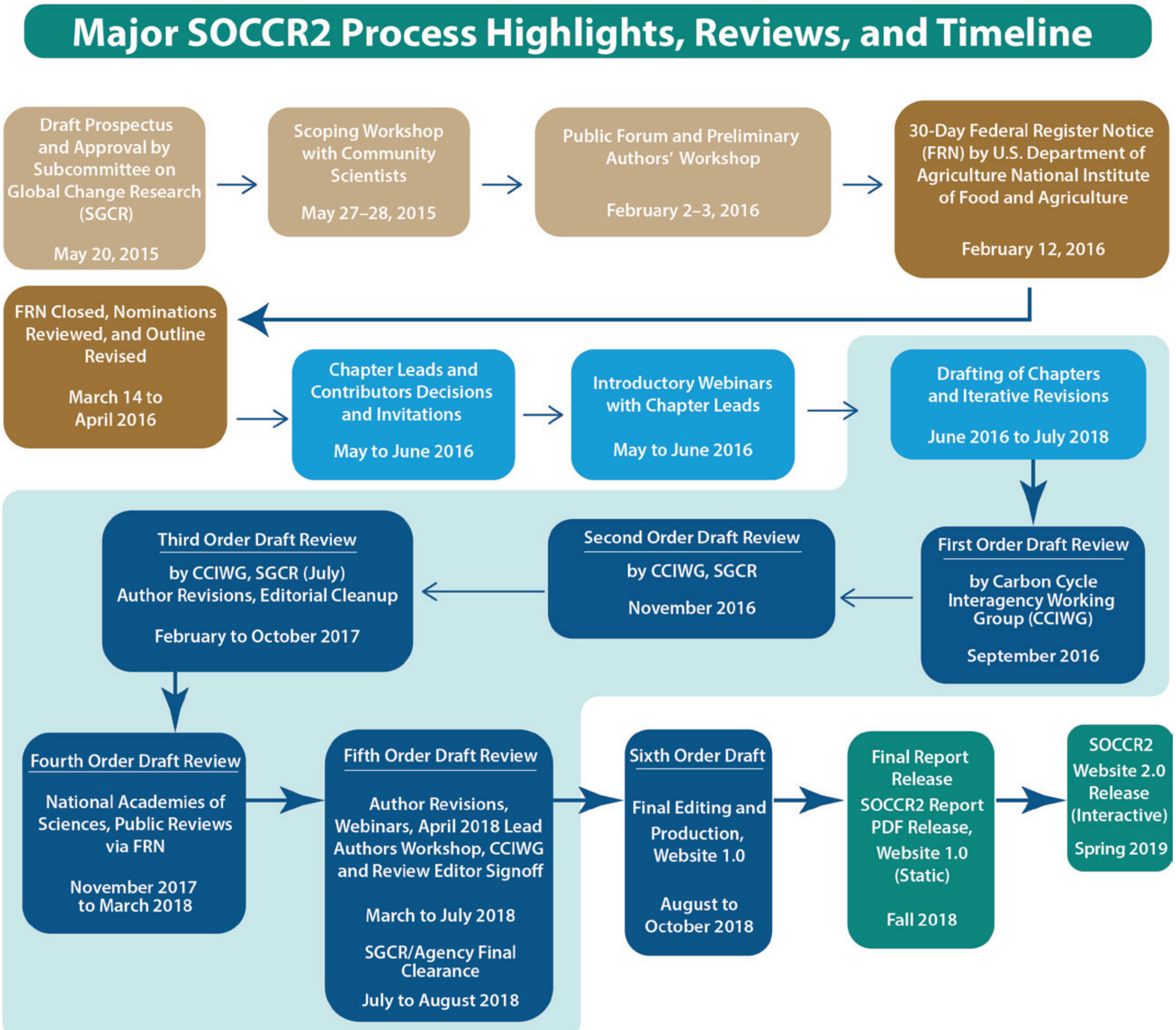

Figure P.1. Major SOCCR2 Process Highlights, Reviews, and High-Level Timeline. Brown boxes denote foundational, developmental stages in the process. Dark blue boxes denote drafting, review, and revision stages.

Guide to the Report

Scientific Framing of the Report

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

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

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

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

Framing of Report

SOCCR2 is framed around the following topics:

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

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

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

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

Author Guidance and Chapter Organization

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

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

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

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

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

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

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

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

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

Geographical Scope

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

Time Frames

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

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

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

Complex Linkages and the Role of Non-Climate Stressors

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

Frameworks for Carbon Accounting

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

Methods for Estimating Carbon Stocks and Fluxes

The SOCCR2 author teams assessed research findings based on three observational, analytical, and modeling methods to estimate carbon stocks and fluxes: 1) inventory measurements or "bottom-up" methods, 2) atmospheric measurements or "top-down" methods, and 3) ecosystem models (see Appendix D, p. 834, for details). "Bottom-up" estimates of carbon exchange with the atmosphere depend on measurements of carbon contained in biomass, soils, and water, as well as measurements of CO_2 and CH_4 exchange among the land, water, and atmosphere. Examples include direct measurement of power plant carbon emissions; remote-sensing and field measurements repeated over time to estimate changes in ecosystem stocks; measurements of the amount of carbon gases emitted from land and water ecosystems to the atmosphere (in chambers or, at larger scales, using sensors on towers); and combined urban demographic and activity data (e.g., population and building floor areas) with "emissions factors" to estimate the amount of CO_2 released per unit of activity.

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

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

Treatment of Uncertainty in SOCCR2

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

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

Estimating Ranges of Quantitative Values

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

Uncertainty of Numerical Estimates

In many tables and figures, a series of asterisks is used to express the uncertainty of numerical estimates (which may be based on statistical properties or expert judgment):

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

Key Findings and Supporting Evidence

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

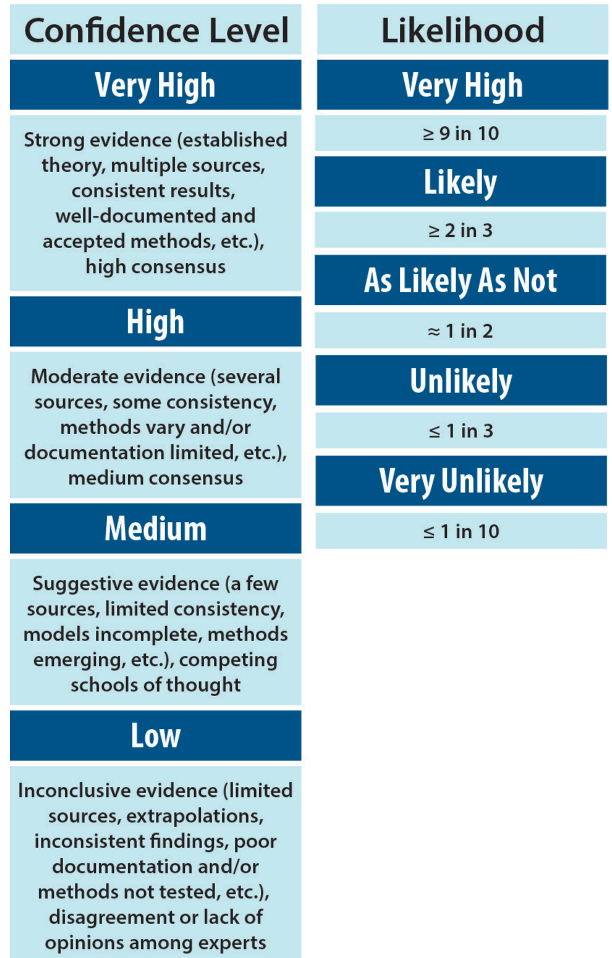

Figure P.2. Likelihood and Confidence Evaluation.

Interagency Context of U.S. Carbon Cycle Science

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

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

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

Box P.3 Maximizing Interagency Coordination

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

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

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