2023 North American Carbon Program Science Implementation Plan

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Chapter 1. Introduction: Motivation, History, Goals, Achievements and Challenges

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1.1 Motivation

Carbon is a building block of life, a central biogeochemical element in the earth system, and an important constituent of Earth's atmosphere as a greenhouse gas (GhG) that powerfully influences global climate. Human activity has radically altered the global carbon balance in fundamental ways, with severe consequences for the Earth system. Vast quantities of carbon have been emitted as CO_2 from oxidation of the primary carbon-containing fuels humans have used over the past two centuries, and from the destruction of natural ecosystems for agriculture, resource extraction, industry, transportation, and other human endeavors. Together these have significantly elevated atmospheric greenhouse gas concentrations, leading to planetary warming and attendant climate changes that are fundamentally altering ecosystems and environments worldwide. They have also acidified the oceans, jeopardizing coral reefs, endangering fisheries, and threatening the extinction of many species. Many of these impacts involve adverse natural feedbacks that release additional greenhouse gases and accelerate climate change. There is a pressing need to understand these changes to the global carbon cycle and their interactions with the climate system and biosphere so that we may stabilize and reverse their damaging impacts and safeguard human well-being and life on planet Earth. The North American Carbon Program (NACP) responds to continued and growing urgency to understand these dynamics and drivers of the coupled carbon-climate system, and its interactions with the health and sustainability of ecosystems, natural resources, and the provisions of goods and services.

1.2 The North American Carbon Program

With a focus on sources and sinks of carbon for North America and its coastal waters (Figure 1.1), the North American Carbon Program emphasizes diagnosis of the contemporary carbon cycle, scientific understanding of how it responds to natural and human forcings, and skillful predictions of its likely future dynamics. The program also aims to provide scientific assessments of a range of policy and management options being considered to mitigate climate change and ocean acidification by protecting and expanding land, aquatic, or oceanic carbon stocks. As such, the NACP plays a vital role in global carbon cycle research and its applications in service to society.

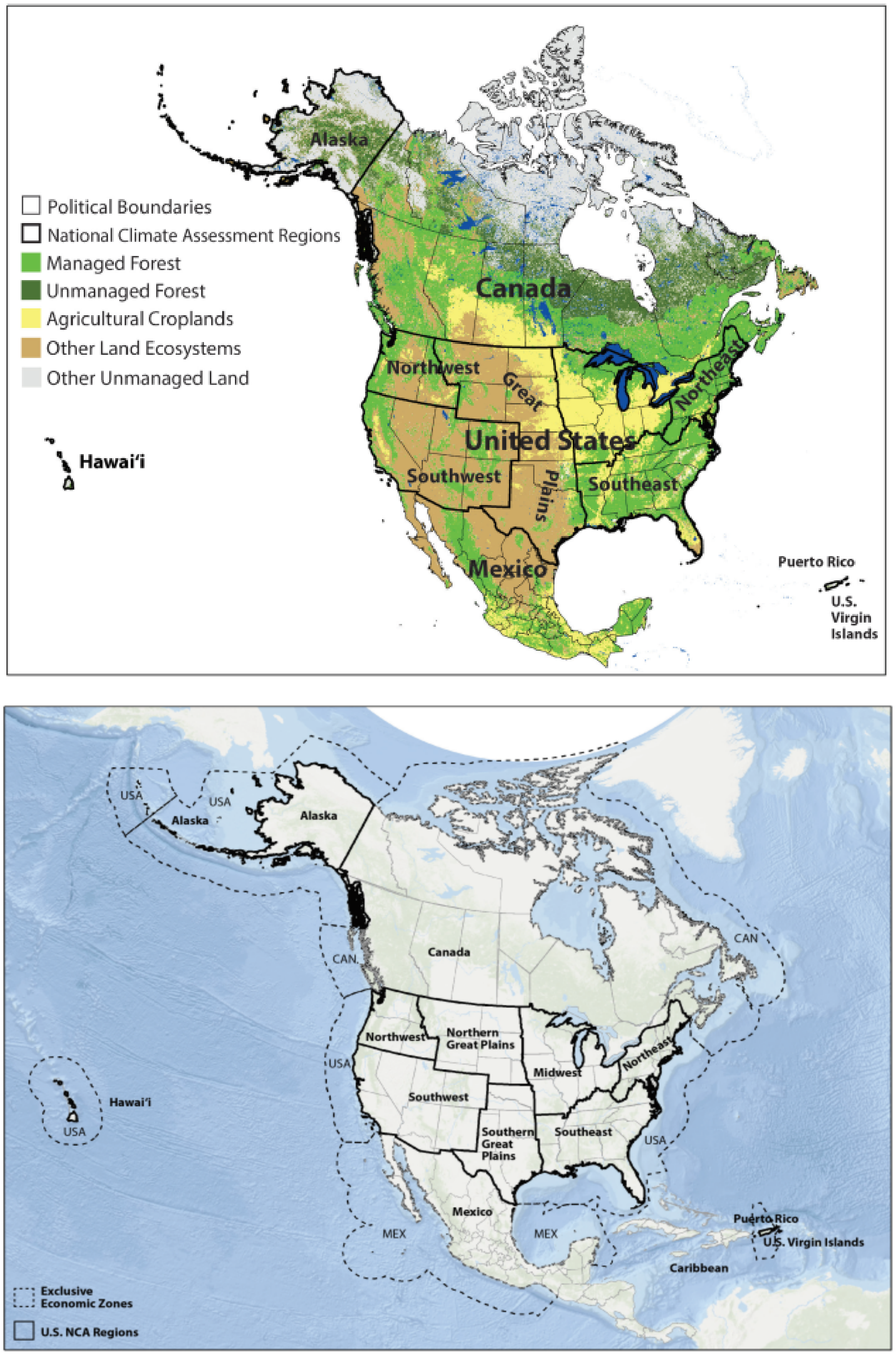

Figure 1.1. Domains for the Principal Activities of the North American Carbon Program.
(a) Broadly represented in this map are the general carbon cycle sectors of forests, agriculture, other lands, and coastal regions intersected by the national terrestrial boundaries of Canada, the United States, and Mexico. [Figure reproduced from the Second State of the Carbon Cycle Report (SOCCR2), Chapter 2 (Hayes et

al. 2018), p. 75. Data source: Sector coverage is based on land-cover data developed by Wei et al. (2013) for the model-inventory comparison study of the North American Carbon Program regional interim synthesis.]
(b) In addition to the land masses and inland waters, the NACP covers carbon dynamics in coastal waters, defined as tidal wetlands, estuaries, and the coastal ocean, the latter being defined by the Exclusive Economic Zone (EEZ). The seaward boundary of the EEZ is typically 200 nautical miles from the coast. The geographic scope of the US domain includes the conterminous United States, Alaska, Hawai'i, Puerto Rico, and the US Virgin Islands. [Figure reproduced from SOCCR2, Executive Summary, Figure ES.1. Figure source: Christopher DeRolph, Oak Ridge National Laboratory.]

1.3 Program Foundation and Developmental History

The North American Carbon Program (NACP) began as a principal activity of the US Carbon Cycle Science Program (USCCSP). Born out of the 1999 US Carbon Cycle Science Plan (Sarmiento and Wofsy, 1999) (Figure 1.2), the NACP was established in 2002 in response to the NACP Report (Wofsy and Harris 2002). Since its inception, the NACP has become an essential venue for coordinated US measurement and research concerning terrestrial, aquatic, and coastal ocean carbon fluxes, their importance as sources and sinks of atmospheric greenhouse gases (primarily CO_2 and CH_4), and the extent to which they both affect and are affected by natural processes and human activities. While the NACP emphasizes US contributions to global carbon cycle science along with partners across North America including Canada, Mexico, and Indigenous Nations, the program's observations, analyses, and findings have relevance and impact at the global scale.

Shortly after the program's establishment, a 2005 NACP Science Implementation Strategy (Denning et al. 2005) outlined an initial phase of activity that emphasized diagnostic studies to uncover carbon source and sink trends, and attribution studies to identify the processes responsible for these trends. The 2005 strategy document also identified activities needed to advance predictive capability and to support decision makers, with an anticipated developmental progression to expand the program's scope in these areas over time.

In 2011, the US Carbon Cycle Science Plan revisited the USCCSP science goals (Michalak et al. 2011), reiterating broad research priorities and new directions. As a follow-on effort, this NACP Science Implementation Plan (NSIP) revises and updates the 2005 NACP strategy document. It responds to new scientific capabilities, the program's developmental progression, and emergent priorities.

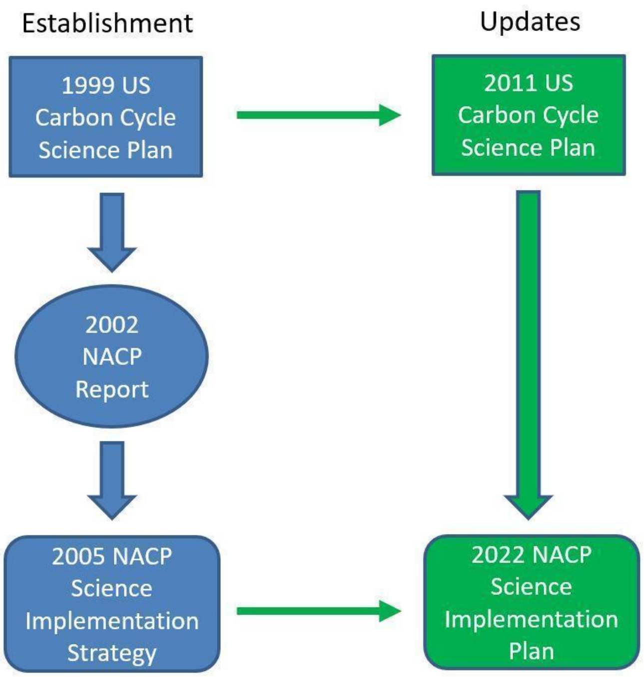

Figure 1.2. Establishment of, and updates to, the North American Carbon Program (NACP), from its origins in the US Carbon Cycle Science Plan to its design laid out in science implementation documents.

1.4. The 2023 NACP Science Implementation Plan

This 2023 NACP Science Implementation Plan highlights key gaps and offers strategies for program implementation. The intention is to facilitate coordinated, complementary, and comprehensive science research activities that address the major goals of the NACP (Chapter 2). This new plan builds on the foundation of the 2005 NACP Science Implementation Strategy to design an up-to-date research program that responds to emerging research needs, recent discoveries, and new capabilities.

The plan reviews key activities needed for a full implementation of the NACP's broad science goals, and highlights selected activities deemed to be of highest priority. The plan's activities are organized among five overarching program elements that are introduced in Chapter 2 and given more detail in Chapter 3. Highest priority is based upon three main criteria: the largest uncertainties, the weakest understanding, and the greatest public need.

The plan also reviews major achievements of the program to date (Section 1.8), provides a vision for sustaining and strengthening collaborative linkages to diverse partners and institutions (Chapter 4), and identifies data and information management capabilities needed to support the overall program (Chapter 5).

1.5 Comments on Procedure, Audience, and Distribution

The NSIP was developed by a leadership team consisting of leads or co-leads for each of the major implementation themes (Program Elements), and an overall chair who guided the activity, with logistical support provided by the NACP Coordinator located in the Carbon Cycle & Ecosystems Office. Together, this team led the plan's development to design a balanced science program that considers advances in research and technology, program gaps, and emerging issues while highlighting new activities of the highest priority. The team engaged in discussions with the NACP Science Leadership Group (SLG), sought input from the broad NACP community, assembled writing teams to draft the plan, facilitated public review by the NACP community, and revised the plan in response to these reviews. As such, the NSIP document has been prepared principally by the diverse community of scientists engaged with the NACP.

The NSIP has been developed to guide the research science community of the NACP. It is also available to provide information for interested government agencies including those participating in the Carbon Cycle Interagency Working Group (CCIWG), the US Global Change Research Program (USGCRP) science community and associated executive branch entities, and other institutions in the private sector and the nonprofit sector, including science organizations. Formal delivery of the plan involved distribution to the NACP Science Leadership Group, the CCIWG, and any interested party, with broad public release.

1.6 NACP Science Questions and Goals

Many of the goals, questions, program elements, and deliverables articulated in the NACP's founding documents (Wofsy and Harris 2002; Denning et al. 2005) remain central to the program today. This plan increases emphasis on process-oriented understanding, predictive capabilities, and decision support. Here we briefly restate the program's founding science questions and goals, and its founding developments and intended deliverables.

Science Questions and Goals

This 2022 NACP Science Implementation Plan adopts the science questions stated in the 2011 US Carbon Cycle Science Plan (Michalak et al. 2011) with only modest revision.

NACP Science Plan Questions

How do natural processes and human actions affect the carbon cycle on land, in the atmosphere, and in the oceans?

How do policy and management decisions affect the levels of the primary carbon-containing gases, CO_2 and CH_4, in the atmosphere?

> *How are ecosystems, species, and natural resources impacted by increasing greenhouse gas concentrations, the associated changes in climate, and by carbon management decisions?*

To answer these overarching questions the initial NACP Report (Wofsy and Harris 2002) outlined the following program goals.

Original NACP Goals

> *"… to provide the scientific information needed to inform policies designed to reduce contributions by the US and neighboring countries to atmospheric carbon dioxide and methane."*
>
> *"… to provide scientific data to determine the fate of CO_2 emitted to the atmosphere by combustion of fossil fuels. It is also aimed at comprehensive understanding of the rates and mechanisms controlling carbon uptake and release from soils and vegetation in North America and the adjacent Atlantic and Pacific Oceans"*
>
> *"… to reduce uncertainties about the carbon cycle component of the climate system, and to develop scientific and technical tools to forecast future increases in concentrations of atmospheric CO_2 and CH_4."*
>
> *"…to provide scientific information needed to design effective and economical policies for the US and neighboring countries to manage carbon sources and sinks."*

A follow-on science implementation strategy (Denning et al. 2005) articulated similar goals but with additional language about the need to inform management and policy decisions affecting carbon emissions, to provide information on optimal strategies for carbon sequestration, to provide the scientific basis for implementing full carbon accounting, and to provide the scientific understanding needed for projections of future carbon fluxes as they respond to climate, energy policy, and land use.

More recently, the US Carbon Cycle Science Plan provided updated programmatic aims (or goals), restated here with only modest revision for the North American Carbon Program.

2023 NACP Goals

> **1)** *Document past and current concentrations of atmospheric CO_2 and CH_4 and surface fluxes of CO_2 and CH_4, and provide clear and timely explanation of their variations and uncertainties.*
>
> **2)** *Understand and quantify the socioeconomic drivers of carbon emissions, and develop transparent methods to monitor and verify those emissions.*

> **3)** *Determine and evaluate the vulnerability of carbon stocks and flows to future climate change and human activity, emphasizing potential positive feedbacks to sources or sinks that make climate stabilization more critical or difficult.*
>
> **4)** *Predict how ecosystems, biodiversity, and natural resources will interact with* CO_2 *and climate change forcings to affect carbon cycling.*
>
> **5)** *Examine a wide range of potential carbon management pathways that might be undertaken to achieve a low-carbon future, and determine their likelihood of 'success' and side effects*.
>
> **6)** *Address decision maker needs for current and future carbon cycle information with relevant and credible data, projections, and interpretations.*

1.7 Review of Founding Documents and Intended Deliverables

The NACP's founding documents identified several high priority general developments needed to deliver on the program's overall goals (Wofsy and Harris 2002) as:

> *"… quantitative scientific knowledge, robust observations, and models to determine the emissions and uptake of* CO_2*,* CH_4*, and CO, the changes in carbon stocks, and the factors regulating these processes for North America and adjacent ocean basins*."
>
> *"… the scientific basis to implement full carbon accounting on regional and continental scales. This is the knowledge base needed to design monitoring programs for natural and managed* CO_2 *sinks and emissions of* CH_4."
>
> *"… long-term quantitative measurements of sources and sinks of atmospheric* CO_2 *and* CH_4*, and develop forecasts for future trends*."

The early plan envisioned three phases of development, moving from initiation, to testing and implementation, and to operation. Also, it identified enabling developments of highest priority:

> *(1) the development of in situ sensors and sampling protocols;*
>
> *(2) performance of modeling studies to inform network design;*
>
> *(3) advances in model-data fusion and integration to diagnose and attribute carbon sources and sinks;*
>
> *(4) optimization of national inventories for carbon accounting;*

> *(5) strengthening current observation networks to fill gaps in long-term measurements of greenhouse gases and to transform AmeriFlux into an integrated, near-real time network;*
>
> *(6) improve databases documenting fossil fuel uses, land use, and land cover;*
>
> *(7) the development of remote sensing technology for measuring greenhouse gases, biomass, and soil moisture.*

Key deliverables of the program were envisioned as:

> "*measurements of sources/sinks for CO_2, CH_4, CO for North America and adjacent ocean basins, at scales from continental to local with seasonal resolution.*";
>
> "*attribution of sources/sinks to contributing mechanisms, including climate change, changes in atmospheric CO_2, nutrients, pollutants, and land use history.*";
>
> "*documentation of North America's contribution to the Northern Hemisphere carbon budget, placed in the global context.*";
>
> "*optimized sampling networks (ground-based and remote) to determine past, current, and future sources and sinks of CO_2, CH_4, CO, and major pollutants*";
>
> "*data assimilation models to compute carbon balances*";
>
> "*A State of the Carbon Cycle Report (SOCCR) as periodic report communicating results to the public*"; and,
>
> "*data and observations to enable major advances in atmospheric chemistry, resource management, and in weather forecasting and climate models.*".

Major progress has been made addressing the NACP's science goals, priority enabling developments, and key deliverables. Progress to date as well as continuing and emerging needs are reviewed in Chapter 2, followed by more detailed plans for the future of the program presented in Chapter 3.

1.8 Achievements and Remaining Challenges

Major progress has been made in delivering the NACP's fundamental research agenda as originally conceived, with contributions from a widespread and diverse collection of individuals and institutions. Today's scientific and technical capabilities and current understandings show clear traces of the program's early plans, with notable progress on all of the enabling developments and key deliverables.

An initial core of observations has been deployed to document concentrations of carbon species in the atmosphere and oceans (e.g. Figure 1.3), including NOAA's core Global Monitoring Laboratory, Pacific Marine Environmental Laboratory, and Atlantic Oceanographic and Meteorological Laboratory, essential for estimating carbon sources and sinks at monthly to decadal time scales and over regional to continental spatial scales. Atmospheric sampling with tall towers is now being complemented by new observations on aircraft, ships and floats, and with spaceborne, remote detection of greenhouse gas concentrations.

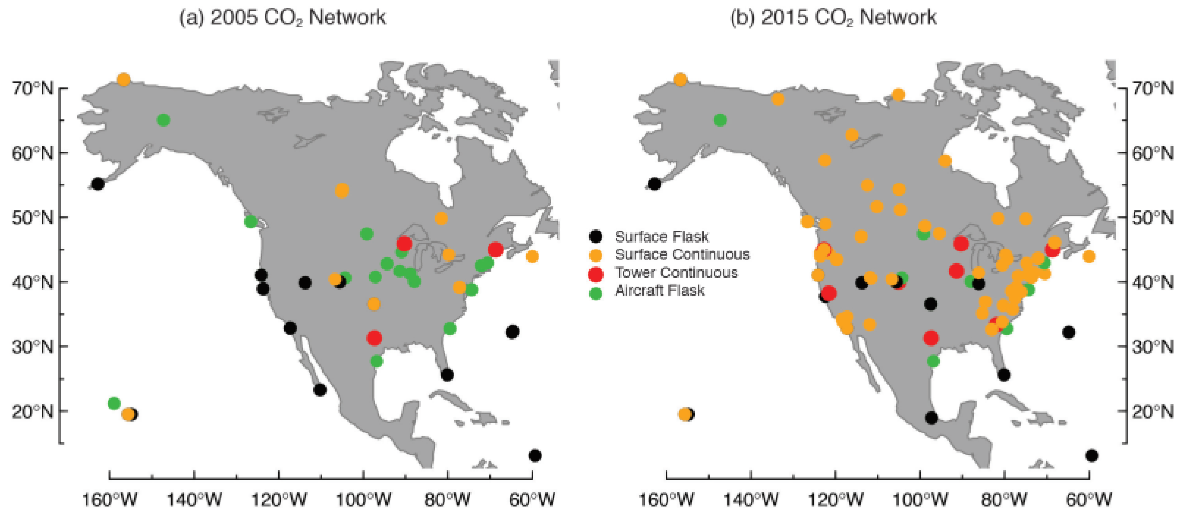

Figure 1.3. Growth of the North American Carbon Dioxide (CO_2) Monitoring Network from (a) 2005 to (b) 2015. Many National Oceanic and Atmospheric Administration aircraft sites were terminated after 2005. Unlike "surface" sites, "tower" sites generally have inlets 100 m to 400 m above the surface. About 90% of both tower and surface sites also report methane measurements. [Figure reproduced from SOCCR2, Chapter 8 (Jacobson et al. 2018), Figure 8.2, p. 341].

National inventories tracking carbon dynamics in forestlands, rangelands and croplands have been improved with new and expanded sampling protocols. Flux tower networks, such as AmeriFlux and MexFlux, continue to grow, supported in part by US Department of Energy coordination and also including important connections to the National Ecological Observing Network.

Spaceborne and airborne remote sensing capabilities have been deployed to study and monitor a wide range of biospheric, atmospheric, oceanic, hydrospheric and geologic states and behaviors that are critical for understanding of the carbon cycle. They monitor vegetation biomass and structure, photosynthetic activity on land and in water bodies, soil moisture, ecosystem disturbances, land use and land cover changes, hydrologic inundation, and much more. A wide range of ecological, meteorological, and hydrological ground-based networks monitor a similar suite of attributes but often with finer scale and greater detail. This includes critical contributions from programs such as the US Department of Agriculture (USDA) Forest Service Forest Inventory and Analysis, the USDA National

Agricultural Statistics Service, the USDA Natural Resources Conservation Service Rapid Carbon Assessment, and the US Geological Survey (USGS) Groundwater, Streamflow and Water Quality Monitoring programs.

The National Aeronautics and Space Administration (NASA) established a program to develop a prototype Carbon Monitoring System (CMS) leveraging existing observations from across NASA and other agencies, along with additional targeted measurements conducted by some individual projects, to demonstrate potential new data products or applications. The NASA CMS science team includes researchers from across NASA and from other agencies and universities and has strong links with the NACP. Accomplishments include the development of continental US biomass data products and a global carbon flux product, as well as demonstrations of Monitoring, Reporting and Verification (MRV) in support of local- and regional-scale carbon management projects; scoping of potential new ocean carbon monitoring products; and engagement of carbon monitoring user-communities to better understand their needs for carbon data and information products. NASA CMS has developed a state-of-the-science data assimilation system that integrates satellite and surface observations related to anthropogenic, oceanic, terrestrial and atmospheric carbon.

Multi-agency efforts have put increasing focus on quantification of anthropogenic sources of GHGs. Dramatic progress has been demonstrated in quantifying GHG emissions from cities, agricultural and industrial processes. Notable programs include the National Institute of Standards and Technology (NIST)'s urban testbed program, multi-agency efforts to quantify methane emissions from the natural gas supply chain, and extensive testing of remote-sensing technologies able to measure both regional emissions and emissions from large point sources.

Databases documenting fossil fuel and cement emissions, such as the early Carbon Dioxide Information and Analysis Center (CDIAC) (Figure 1.4) that is now replaced by Environmental Systems Science Data Infrastructure for a Virtual Ecosystem (ESS-DIVE), have seen continued improvements in spatial resolution and with the chemistry of fuels, for example with The Vulcan Project. Datasets documenting carbon emissions from land use and land change have been improved with more detailed understanding of the nature and extent of land use and change, associated perturbations to carbon stocks, and ensuing carbon emissions legacies.

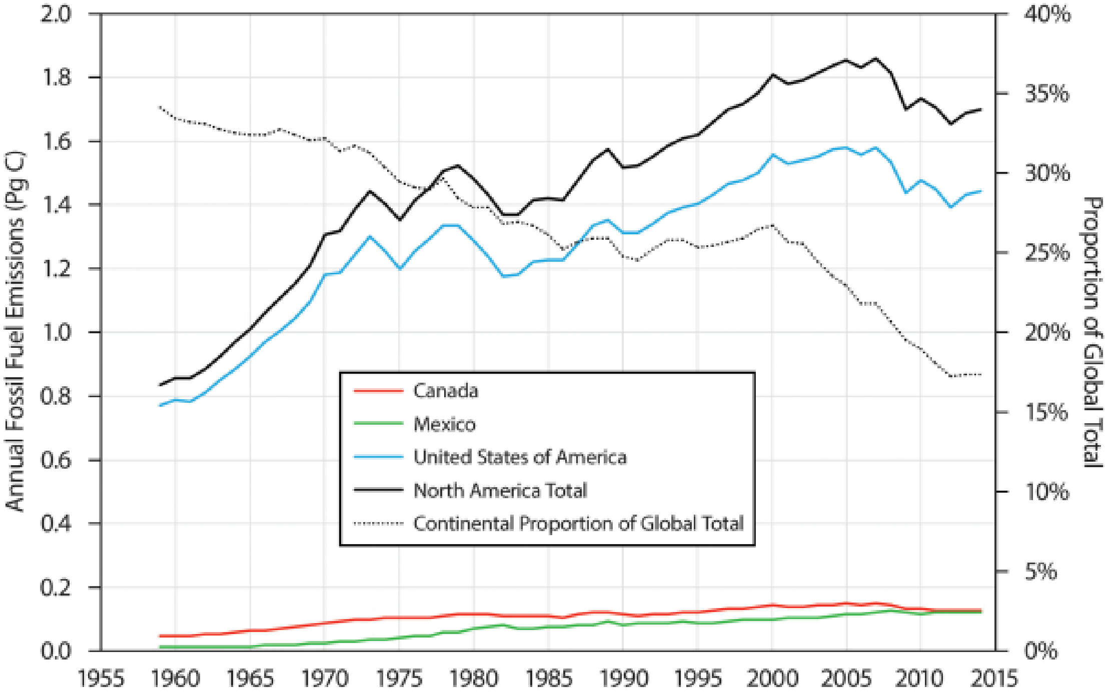

Figure 1.4. Annual North American Fossil Fuel Emissions from 1959 to 2014. Values are given in petagrams of carbon (Pg C) for each country and for the continent as a whole (solid lines, left vertical axis). The dotted line shows the North American proportion of the total global emissions (right vertical axis). [Figure reproduced from the Second State of the Carbon Cycle Report (SOCCR2) Executive Summary (Birdsey et al. 2018), p. 29. Data source: Carbon Dioxide Information Analysis Center (Boden et al., 2017)]

Carbon dynamics in riverine, lake and wetland systems have received increased attention, with new analyses and observing systems that are improving understanding of net carbon exchange with the atmosphere, and lateral fluxes and transformations.

Together these advances have supported comprehensive assessment of the major carbon fluxes of North America (Figure 1.5). Better scaling, synthesis, and integration of disparate and diverse data types has enabled improved carbon accounting and monitoring. Progress has been made in data assimilation systems and in modeling of atmospheric transport, both of which have improved top-down inversions of atmospheric data being used to infer surface sources and sinks of carbon species at regional to global scales. Data integration and model-data fusion techniques have improved, expanding capacity for diagnosing and attributing carbon sources and sinks. Advances in attributing carbon dynamics to specific mechanisms have been made, enhancing capacity to trace human activities and their impacts on carbon dynamics through the changes in climate, atmospheric composition, and land cover and use. These innovations appear to be leading to improved agreement and reduced uncertainties among top-down atmospheric-based and bottom-up inventory-based assessments and computational model-based estimates of continental-scale net land-atmosphere exchange of carbon dioxide (Figure 1.6).

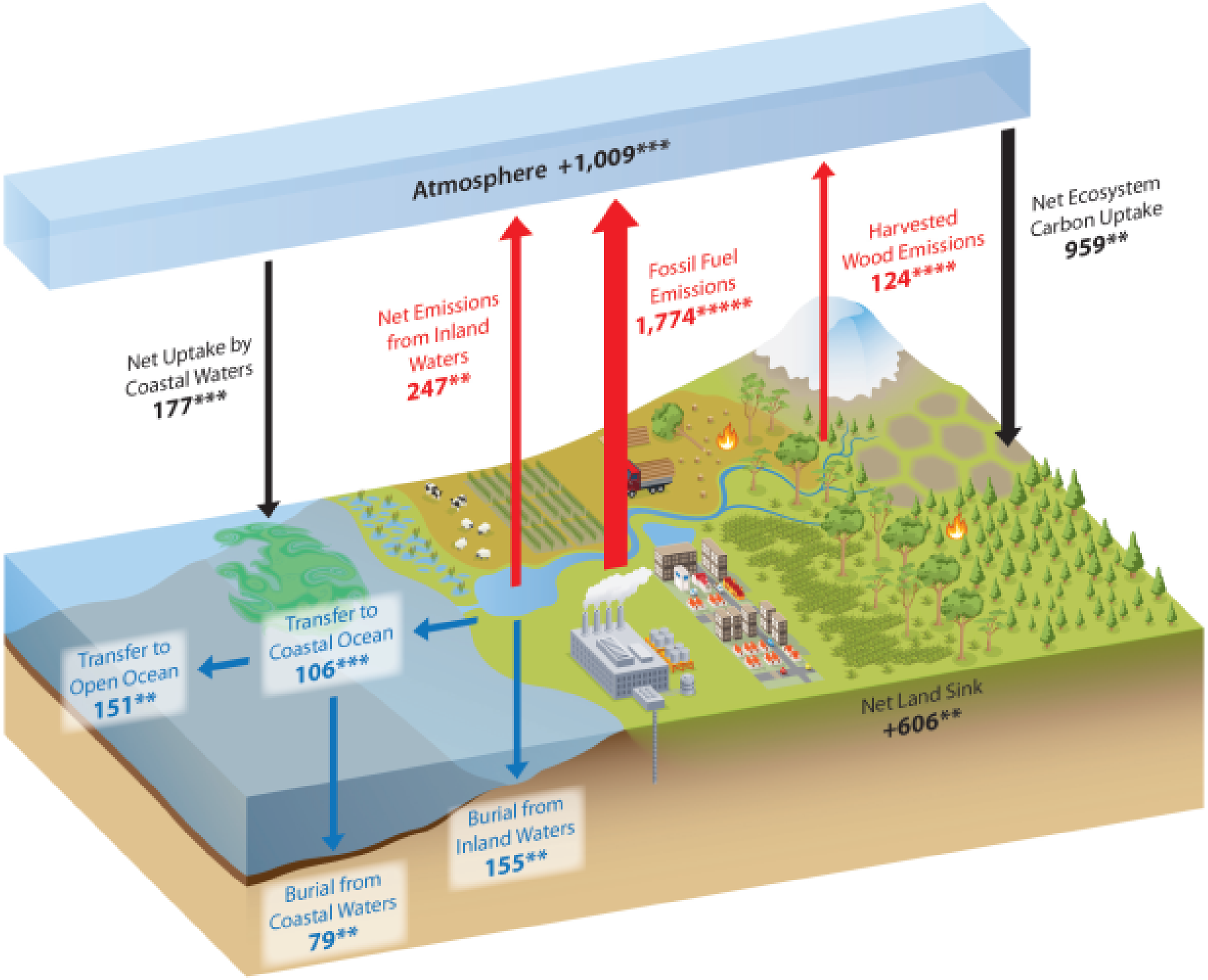

Figure 1.5. Major Carbon Fluxes of North America as reported in SOCCR2. [Figure reproduced from the SOCCR2 Executive Summary (Birdsey et al. 2018), Figure ES.2, p. 26]

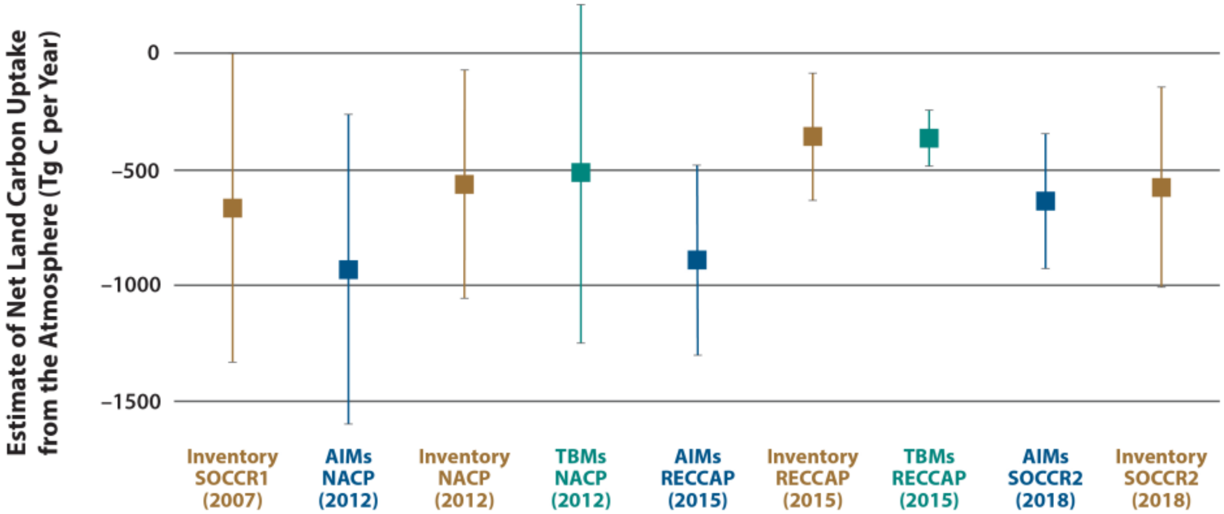

Figure 1.6. Estimates of the North American Carbon Sink in this Century. Estimates, in teragrams of carbon (Tg C) per year, are derived from inventory analysis, atmospheric inversion models (AIMs), and terrestrial biosphere models (TBMs). Publication year of each estimate is given in parentheses. [Figure reproduced from the SOCCR2, Chapter 2 (Hayes et al. 2018) , Figure 2.5, p. 94. Data sources: First State of the Carbon Cycle Report (SOCCR1; CCSP 2007), North American Carbon Program (NACP; Hayes et al. 2012), Regional Carbon Cycle Assessment and Processes (RECCAP) initiative (King et al., 2015), and Second State of the Carbon Cycle Report (SOCCR2) (Hayes et al. 2018)]

Large-scale research intensives have been launched (e.g. Mid-Continent Intensive, the Arctic-Boreal Vulnerability Experiment (ABoVE), the Atmospheric Carbon and Transport-America study (ACT-America)), revealing insights about the carbon metabolism of natural ecosystems, agrosystems, and built environments, and how it relates to human activity and environmental variability.

New manipulative experiments have been activated. As just one example from an US NSF LTER Network site, Harvard Forest has offered decades-long experiments of soil warming, simulated hurricane damage, and nitrogen addition. We also highlight several experiments launched relatively recently that are well positioned to provide new, important insights, including SPRUCE, NGEE-Arctic, and NGEE-Tropics. These and other developments are improving understanding of carbon cycle feedbacks and carbon stock vulnerabilities, such as forest mortality, climate-induced carbon losses from peatlands and the thawing of carbon-rich permafrost soils.

Predictive modeling has advanced, with new capabilities emerging from the development of benchmark datasets for model evaluations, from model intercomparison activities, from model assessment with emergent constraints, from inclusion of new model theory, from improved integration of socioeconomic and natural/physical processes that jointly affect the global carbon cycle, and from model applications to assess impacts of interactive global change drivers, feedbacks and vulnerabilities (e.g. permafrost). Integrated assessments now provide better fusion of social, economic, ecological, and physical factors in their characterizations of possible future pathways.

The NACP has engaged in extensive reporting, communication and outreach activities. These include major contributions to USGCRP synthesis reports including two rounds of the Sustained Assessment Report on the State of the Carbon Cycle Report (SOCCR) published in 2007 and 2018, as well as two rounds of the National Climate Assessment (NCA) published in 2014 and 2018. NACP researchers have contributed to the Global Carbon Project, including its Regional Carbon Cycle Assessments and Processes (RECCAP) initiative and annual Global Carbon Budget publications (e.g. Friedlingstein et al. 2022). Also, the NACP has a presence at many national and international science conferences, and hosts its own open science meetings roughly every third year.

The program has included well over 500 research projects with affiliations, associations, and linkages extending well beyond these individual pieces of science.

While these achievements are to be celebrated, much work needs to be done to fulfill the program's aims. Holes in measurement networks and limited capacity for integration hinder diagnosis and attribution. Gaps in process understanding yield major uncertainties for diagnosis and prediction. Underdevelopment of the program's communications, outreach, and decision support dimensions undermines the program's ability to inform the public and address decision maker needs. Expanded reach is needed to be more inclusive of activities, efforts and participants across all of North America.

It is also important to draw attention to several threats to the work of the NACP. While some sampling networks have grown, others have seen significant reductions, including FLUXNET-Canada, the USGS hydrological monitoring network, and NOAA's atmosphere and ocean sampling networks, though NOAA is currently working to strengthen and expand its capacity. Much of our understanding of the carbon cycle emerges from measurements sustained over decades. Supporting long-term observational records continues to be a challenge, as research ventures need to be transitioned to operational capacities. Historically, funding from short-term grants has been strung together to create long-term observational records, and new funding models are needed to support carefully planned and coordinated sustained observations. Additionally, restructuring and relocation of some federal institutions such as the USDA ARS, and some USDA FS, and USGS offices has jeopardized the critical contributions these institutions make to carbon cycle research.

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Chapter 2. Program Elements and Leading Initiatives for the Future

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This Chapter outlines the NACP's contemporary program elements needed to deliver on the program's goals followed by highlights of some of the highest priority leading initiatives for the program's future.

2.1 The 2023 NACP Program Elements

The 2005 NACP Science Implementation Strategy outlined a series of intersecting Program Elements necessary for achieving the original goals of the NACP. Those elements are closely mirrored in this new implementation plan but are given expanded scope and have been revised to reflect new developments.

The 2022 NACP Program Elements are:

Sustained and Expanded Observations (Chapter 3.1) seeks to measure surface biogenic and anthropogenic carbon exchanges, associated changes in carbon stocks, and their primary social, environmental, and ecological determinants. Observations support evaluation of trends and diagnosis of their drivers (causal factors). Observations also provide scientific data records needed to monitor the effectiveness of carbon policy and carbon management actions.

Integration, Synthesis and Assessment (Chapter 3.2) seeks to produce key scientific data products and to develop analytical methods needed for integration and assessment activities that bridge across scales and across disparate observations and disciplines. Assessment and integration activities advance core scientific understanding of contemporary carbon cycle trends and provide the basis for communicating these findings to broad audiences.

Processes and Attribution (Chapter 3.3) seeks to uncover mechanistic drivers of carbon cycle dynamics, including the processes that underlie their responses to societal and environmental changes. In doing so, it provides a process-oriented understanding of recent trends as well as the theoretical and empirical foundations for skillful predictions.

Prediction (Chapter 3.4) seeks to develop and test predictive understanding of the carbon cycle to identify and resolve processes missed or poorly represented in models, and then to apply improved models to generate insights into expected behaviors of the carbon cycle in the future as a dynamic and interactive component of the full Earth System.

Communication, Coordination and Decision Support (Chapter 3.5) seeks to facilitate clear and effective communication of current understandings of how the carbon cycle is responding to drivers now and how it will in the future, to reach diverse audiences including non-specialists. In addition, it seeks to develop decision support tools that aid private sector and public sector decision makers with exploring the impacts of policy and management options.

Chapter 3 details each Program Element with a comprehensive set of critical activities needed for full implementation. Important advances, challenges, gaps, and emerging issues are identified for each, and highest priority activities and developments are highlighted. In addition, this chapter emphasizes the highest-level needs and initiatives for the program's future.

2.2 Leading Initiatives for the Future of NACP

The following five initiatives have been identified as being of highest priority for the program's future.

1. Sustained, long-term observations and research networks are needed as a critical backbone of the NACP in the future, measuring carbon fluxes and stocks in air, land, water, and built environments. These observations are essential for detecting changes as they unfold over time, and for attributing those changes to forcing factors and underlying processes. They underpin carbon cycle science in service to society, with data and information flows tailored to meet today's pressing needs for carbon management in the context of climate change (Figure 2.1).

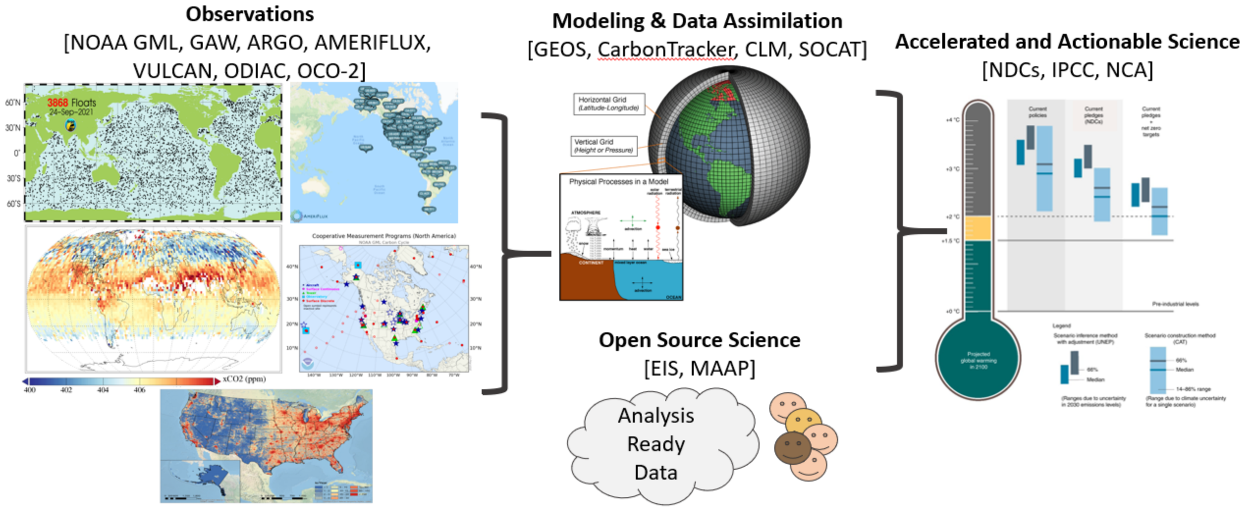


Figure 2.1. Data and Information Flows from Observations to Modeling and Data Assimilation Systems to Policy Makers, Practitioners and Civil Society. Sustaining and expanding long-term observation and research platforms are essential for reaching the aims of the NACP.

2. A comprehensive Carbon Monitoring System is needed, with the mission of transforming current capabilities into a coherent, comprehensive and coordinated observing and analysis system that reports the current state of the carbon cycle and provides timely detection and attribution of its patterns and trends. The system requires thoughtful design, and will surely involve international and cross-agency partnerships and collaborations with research science institutions, and may require interagency coordination and public-private partnerships (Figure 2.2). It should be designed as an integral contribution to global carbon monitoring and assessment systems, extending across all environmental spheres (atmosphere, ocean, terrestrial, aquatic, urban, cryosphere), all societal sectors (energy, industry, commercial, agriculture), and all range of scales (city, state, regional, continental, global). Its early activities should involve:

- System design for mission-driven analysis and reporting of carbon stocks and flows across scales and sectors, likely involving hierarchically nested frameworks.
- Identification of targeted expansions of observational and analytical capacities needed to deliver on its mission.
- Scientific and technical advances to provide more complete and holistic accounting and reporting, with clear and transparent methods and with internal consistency across sectors and reporting units, and including checks across measurement systems and scales.

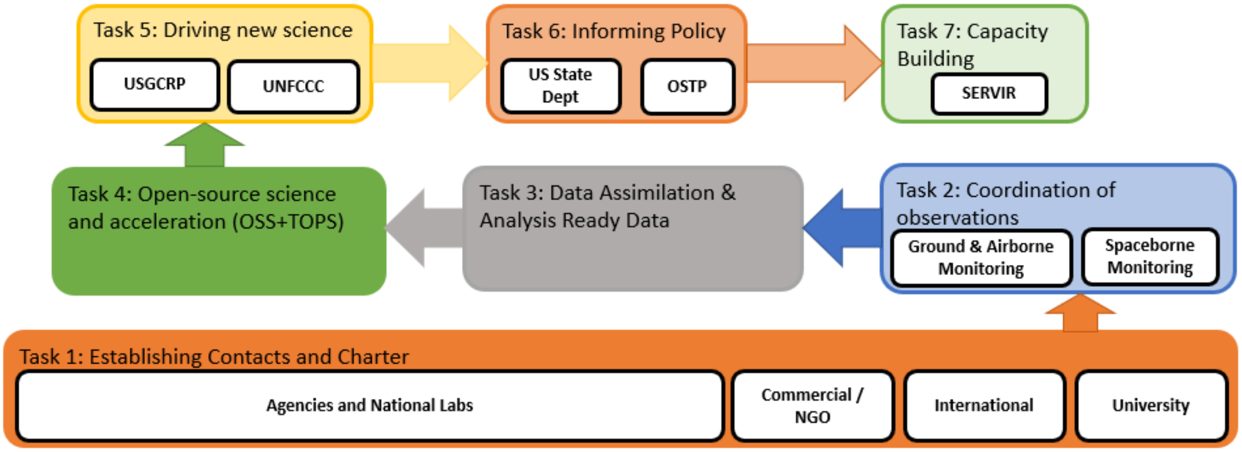
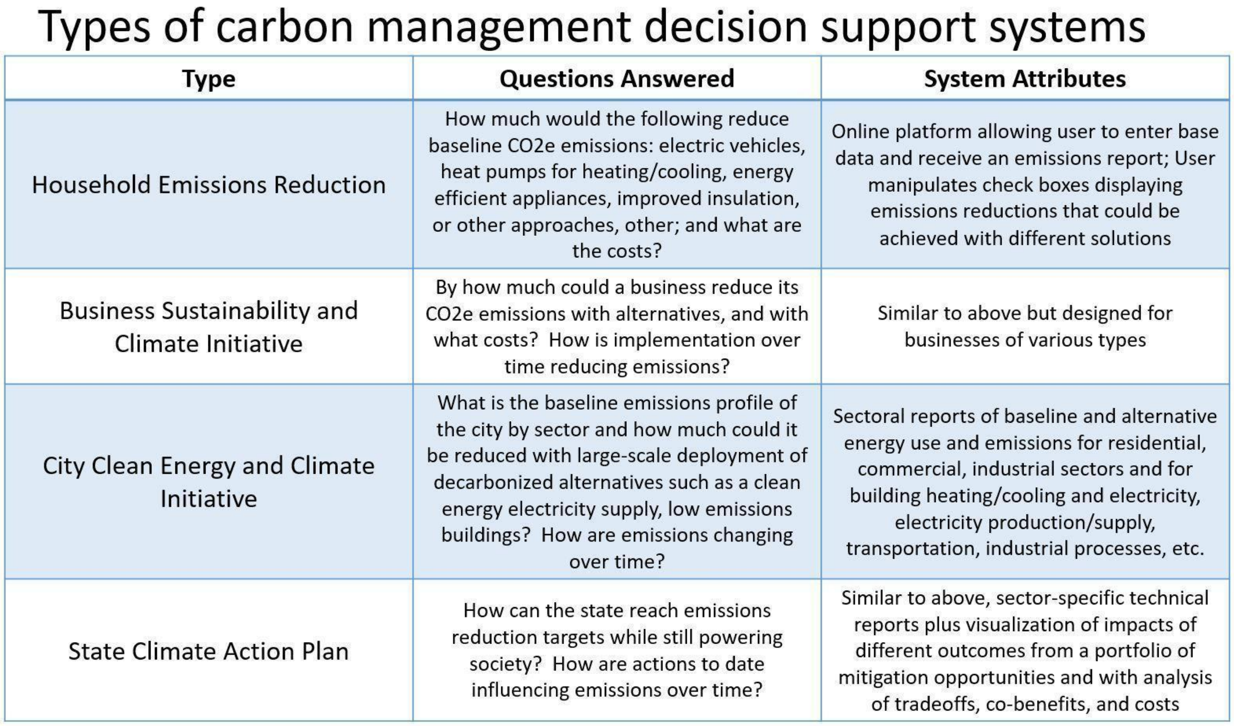


Figure 2.2. Conceptual Illustration of an Interagency Operational Greenhouse Gas Information and Analysis System. Many of the components necessary for an operational greenhouse gas information system exist but a mandate for integration is lacking.

3. A Carbon Decision Support System is needed to answer pressing new questions and needs arising from diverse actors in business, government and civil society (Table 2.1). Its mission will be to enable users to explore opportunities for effective management of C sources and sinks needed for a range of domains such as an individual household, city or state, a select company or industry, or a particular economic sector such as energy or agriculture. It will likely involve cross-agency partnerships and external collaborations. The system (Figure 2.3) will provide land and resource managers, industrial and commercial sectors, and the general public the basic information and tools needed to assess the carbon emissions and removals that might result from specific actions, and associated interactions with the provision of goods and services in society and the environment. Its early activities might involve:

- Examining the societal and environmental impacts of possible transitions to a low carbon, clean energy economy across a range of alternative pathways.
- Establishing a platform to enable users to forecast baseline carbon stocks and fluxes in ecosystems and landscapes given recent trends and with comparison to alternative future scenarios.
- Developing improved approaches to quantifying impacts in a way that standardizes for the scale of actions to demonstrate how even small-scale individual actions can offer meaningful impacts in aggregate when implemented collectively over a much larger scale.
- Mapping the carbon economy, including quantification and visualization of virtual fluxes embedded in production and consumption activities across sectors.



Types of carbon management decision support systems

Type	Questions Answered	System Attributes
Household Emissions Reduction	How much would the following reduce baseline CO2e emissions: electric vehicles, heat pumps for heating/cooling, energy efficient appliances, improved insulation, or other approaches, other; and what are the costs?	Online platform allowing user to enter base data and receive an emissions report; User manipulates check boxes displaying emissions reductions that could be achieved with different solutions
Business Sustainability and Climate Initiative	By how much could a business reduce its CO2e emissions with alternatives, and with what costs? How is implementation over time reducing emissions?	Similar to above but designed for businesses of various types
City Clean Energy and Climate Initiative	What is the baseline emissions profile of the city by sector and how much could it be reduced with large-scale deployment of decarbonized alternatives such as a clean energy electricity supply, low emissions buildings? How are emissions changing over time?	Sectoral reports of baseline and alternative energy use and emissions for residential, commercial, industrial sectors and for building heating/cooling and electricity, electricity production/supply, transportation, industrial processes, etc.
State Climate Action Plan	How can the state reach emissions reduction targets while still powering society? How are actions to date influencing emissions over time?	Similar to above, sector-specific technical reports plus visualization of impacts of different outcomes from a portfolio of mitigation opportunities and with analysis of tradeoffs, co-benefits, and costs

Table 2.1. Types of carbon management decision support systems required to answer carbon management questions posed by society. The general aim is to provide the scientific basis for decision makers to enact effective policy choices regarding managing future climate change and ecosystem changes associated with changing atmospheric CO_2 and CH_4.

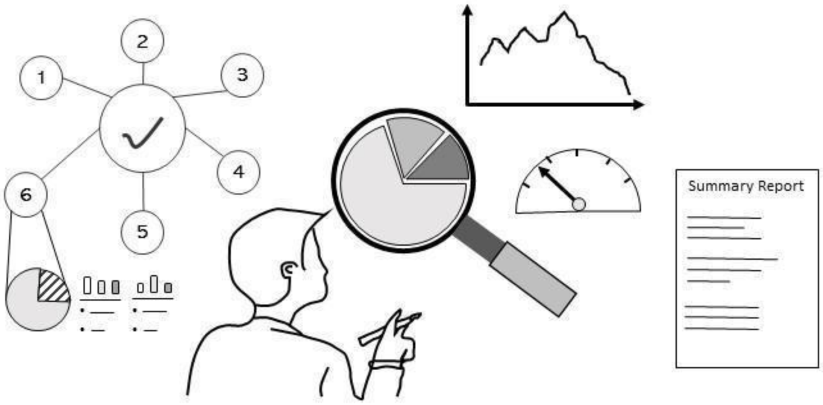


Figure 2.3. Conceptual Illustration of a Carbon Decision Support System designed for household, business, city, or state scales to enable users to access knowledge, information, and understanding about options for carbon management and emissions reductions.

4. Research investments are needed for:

- Sustained, coordinated observations and intensive field campaigns that advance understanding of carbon dynamics along the land-aquatic-oceanic continuum, including holistic assessments of carbon sources, transport, transformation, storage, and exchange with the atmosphere.
- Manipulative global change type experiments that uncover how ecosystems respond to climate extremes and trends, human and natural disturbances, changes in atmospheric composition, and proposed carbon dioxide removal approaches on land and in the atmosphere and ocean. Such experiments need to be designed to falsify key hypotheses about how the coupled carbon-climate system responds to these forcings, with attention to the most influential model hypotheses, maximizing advances in predictive skill as well as uncertainty reductions in long-term forecasts.
- Improving process models with insights emerging from new data sets and with tests that enable rejection of competing process representations, and applying process models to anticipate carbon cycle trends, feedbacks and vulnerabilities.
- Synthesis and integration studies that bridge from discrete, field-scale (<1 ha) measurements of carbon stocks and fluxes to yield spatially and temporally continuous carbon dynamics at larger scales, spanning across ecoregions and functional units to assess landscape, watershed, continental, and Earth System scale patterns.

5. Active communications and outreach are needed to elevate broad awareness about how and why the carbon cycle is changing, the implications of these changes for life on planet Earth, and the actions that could be taken to safeguard our collective future.

Chapter 3.1: Sustained and Expanded Observations

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3.1.1 Introduction

Observations are the foundation of the NACP, needed to detect and attribute changes in the carbon cycle, to elucidate underlying mechanisms and processes, and to enable skillful predictions of the carbon cycle under alternate scenarios of the future. Augmented observing systems are critical to address knowledge gaps identified in the SOCCR2 and in this document.

In the US, responsibility for carbon observations does not reside within a single agency. EPA works with multiple federal agencies to collect and compile data from a number of other departments and agencies and produce an annual Inventory of US Greenhouse Gas Emissions and Sinks as required under the United Nations Framework Convention on Climate Change (UNFCCC). Coordination among agencies making observations to support carbon cycle research occurs primarily via the USGCRP's Carbon Cycle Interagency Working Group. In accordance with guidance from Congress, NASA has established a prototype Carbon Monitoring System (CMS). The NASA CMS leverages existing observation programs from across NASA and other agencies, and some individual projects include additional targeted measurements to develop and demonstrate potential new data products and applications. Many additional US federal programs and agencies make observations of carbon in land, air, and water that are critical for carbon cycle science in North America, including NOAA, USDA, USGS, NSF and DOE.

NACP and NASA CMS have laid the groundwork for a US National Carbon Monitoring System to provide reliable state-of-the-science decision support services to policymakers and diverse stakeholders. A comprehensive and sustained national monitoring effort will require additional high-level coordination and investment across multiple agencies. Guidance from the science community is needed to design an integrated carbon observing system including ground-based, aircraft, ocean, and satellite observations. This could be accomplished through a process similar in scope and influence to the National Academies of Sciences, Engineering, and Medicine's Report: Thriving on Our Changing Planet: Decadal Survey for Earth Science and Applications from Space (National Academies of Sciences, Engineering, and Medicine, 2018). Standardization of methods, automation, and best practices are required to ensure reliable and compatible datastreams nationally and internationally. The observing system should encompass a continuum of effort from

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[1] This chapter is PMEL contribution number 5432

research and development to sustained operations with ongoing engagement of academic, private sector, and federal researchers. System design needs to be flexible and adaptable to ensure continuity of long records while also enabling next generation technology to be deployed. It is beyond the scope of this document to present a full plan for national scale carbon monitoring systems, however Chapter 2 highlights some initial steps needed for their design.

NACP measurements in the context of a global observing system

While NACP is aimed at understanding and quantifying the North American carbon cycle, potential feedback cycles involving large and vulnerable carbon reservoirs outside of the NACP domain drive large uncertainties in global and regional climate forecasts. Furthermore, North American regional estimates depend critically on accurate knowledge of the boundary values. For example, detailed knowledge of the deep ocean carbon budget is a critical gap for estimating continental scale fluxes on decadal scales. Monitoring and process studies to advance understanding of the *global* carbon cycle are thus needed to provide enhanced support for climate policy and mitigation and adaptation efforts by the US and other nations. Sustained and rigorously calibrated measurements are needed to enhance support for implementation of the United Nations Framework Convention on Climate Change (UNFCCC) efforts such as Reducing Emissions from Deforestation and Forest degradation (REDD+) and the Global Stocktakes in 2023 and 2028. Coordinated investments in US and global long-term observing networks will support these efforts and lead to improved models of processes driving regional and global carbon-climate feedbacks.

Several US agencies already contribute to international measurement efforts through programs such as the Committee on Earth Observation Satellites (CEOS), the Group on Earth Observations (GEO), the Global Ocean Observing System (GOOS), and the World Meteorological Organization's (WMO) Global Atmosphere Watch (GAW). NASA, NOAA, and USGS are investing heavily in diverse satellite datasets that are generally global in scope. Continued and expanded coordination with international partners is needed, and measurement strategies, products, and analyses that were prototyped under NACP can now be implemented for other regions via international partnerships. WMO GAW has established an Integrated Greenhouse Gas Observing System (IG^3IS) aiming to expand the observational capacity for greenhouse gases, extend it to the regional and urban domains, and develop the information systems and modeling frameworks to provide information about GHG emissions to society. IG^3IS is not designed to check compliance with regulations, but rather to provide information on policy- and management-relevant scales and ensure that the information provided is consistent with a global network of high quality observations and models. The Global Climate Observing System (GCOS) is a framework to coordinate international efforts and promotes sustained, accurate, and freely available observations. GCOS has described measurement requirements for a comprehensive set of Essential Climate Variables (ECVs) that characterize Earth's climate and has adopted a set of monitoring principles[2]. GCOS recommends targeting efforts to sample data-poor regions and regions sensitive to climate, and calls for carefully planned conversion of research

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[2] Updated ECV measurement requirements are currently under review.

observing systems to long-term operations. Expanded US participation in GCOS and other international efforts will improve efforts for validation and characterization of remote sensing datasets needed to ensure global consistency of products across platforms and over time.

3.1.2 Sustained Observations, Current and Planned

Carbon observing networks should be designed to track responses to interannual variability in climate, long-term trends of climate change as well as human decision making/management through time. Detection of climate change signals requires measurement records of sufficient duration to characterize other sources of seasonal and interannual variability such as anomalies associated with the El Niño Southern Oscillation (ENSO). In addition to testing model parameterizations and inventories, the carbon observing system should detect tipping points and potential surprises. Rapidly changing conditions, especially due to warming in the Arctic and increased frequency of major storms, underscore the urgency of establishing a long-term baseline against which to measure future disturbance and to track the efficacy of regional to international emissions reductions efforts.

The original NACP planning documents (Wofsy and Harris, 2002 and Denning et al., 2005) envisioned a multi-tiered network of terrestrial measurements, including intensive local measurements of carbon stocks and fluxes, with detailed process characterization, forest inventory methods, and remote sensing imagery. An atmospheric observing system consisting of measurements from ground stations, aircraft, ships and buoys was described, and satellite and other remote sensing measurement concepts for atmospheric CO_2 and CH_4 were under development. Estimates of hydrologic transfers of carbon over land, transformations in estuaries and sequestration in coastal oceans were lacking, and estimates of transfers between coastal oceans and open oceans were limited due to sparse data and high variability. Interdisciplinary intensive field campaigns were proposed to test and further develop the long-term observing strategy. Some elements of the planned NACP observing system were realized, while others fell short or evolved in unanticipated ways.

Much progress has been made toward understanding the major components of the North American carbon cycle, including human-induced emissions and the carbon metabolism of society, and recent best estimates of the carbon budget were synthesized in the SOCCR2. A primary objective of the North American Carbon Program was to quantify the land sink. We now know that North American land and aquatic ecosystems and adjacent coastal waters remove an amount of carbon equivalent to 30-40% of North American fossil fuel emissions (SOCCR2 table 8.1, Hu et al., 2019; Liu et al., 2021; Piero et al., 2022), although large uncertainties remain on some components of the budget, particularly those related to transport of carbon through inland waters, wetlands, and estuaries. The lateral flux between land ecosystems and inland waters is an especially large term with uncertainty greater than 100%. Sedimentation and outgassing from inland waters and estuaries are also poorly constrained by the available data, as is exchange between coastal waters and the open ocean. Estimates of these components are complicated by high variability and the role of extreme events such as erosion associated with storms and flooding. Reliable estimates of terrestrial net ecosystem flux are available at local scales (<10 km^2) from intensive measurements at individual sites, and top-down estimates informed by atmospheric observations provide constraints at the continental scale, but large uncertainties remain on net flux estimates at regional scales (10^4-10^6 km^2) due to the complexity of upscaling from the site level and insufficiently dense atmospheric measurements. The current observing system provides insufficient constraints for tracking regional trends in the North American carbon sink, verification of greenhouse gas emissions reduction efforts, and understanding drivers of interannual and interdecadal variability in strength of the terrestrial ecosystem uptake, including assessment of carbon-climate feedbacks and post-disturbance carbon trajectories or shifts in disturbance regimes.

Understanding of the mechanisms driving the North American terrestrial sink remains elusive (SOCCR2 page 349, Section 8.6, Jacobson et al. 2018), and measurements are needed that can distinguish between a potentially short-lived sink due to recovery from past land-use practices (mainly a temperate Northern Hemisphere phenomenon) versus a longer-term sink due to CO_2 fertilization, climate change and nitrogen deposition. Sustained observations are needed to illuminate carbon-climate relationships and to monitor both negative (e.g., extended growing seasons and tree-line migration) and positive (e.g., permafrost carbon release, fire, and insect outbreaks) feedbacks. Climate and carbon impacts on ecosystems must also be monitored, including changes in marine ecosystems in response to ocean acidification and changes in species composition and extent of terrestrial ecosystems. Expanded and improved coordination of observing systems is urgently needed to track rapid changes in the Arctic and other vulnerable regions, especially as we approach potential tipping points that could trigger feedbacks such as the release of carbon from thawing permafrost.

Capacities to detect and attribute human emissions in built environments have improved, including methods to account for the carbon emissions embodied in the production and consumption of material goods and services with global links through international commerce and trade. Expanded datasets are needed for ongoing assessment of mitigation strategies and/or management of climate impacts. For example, many US cities and states have enacted climate action plans that include deep reductions in greenhouse gas emissions, but have relatively limited data and information on how to realize those ambitions. Also, forest carbon datasets are needed at the scale of disturbance and management units to support the design and implementation of effective carbon policy and management aiming to increase carbon sequestration or reduce emissions. Carbon offset programs require trusted and transparent accounting methods supported by verifiable data. Improved and expanded observations will bolster ambitious mitigation efforts from facility to national and global scales.

Current and planned observational capabilities, major findings and decision support services, gaps and limitations, and anticipated measurements and emerging technologies are briefly described as follows.

Atmospheric CO_2 and CH_4

Measurements of atmospheric CO_2 and CH_4 provide an integral constraint for estimating regional surface fluxes and evaluating ecosystem models and inventories using inverse modeling and data assimilation. These top-down estimates of surface fluxes complement bottom-up emissions inventories and estimates of Net Ecosystem Exchange (NEE) from terrestrial ecosystem models and can provide independent information to the extent that atmospheric data is well-calibrated and sufficiently dense, errors in simulated meteorology are unbiased, and "lateral" fluxes are well known (e.g. post-harvest transport of wood products and crops for consumption elsewhere and aquatic transport of carbon via rivers to the coastal ocean). Isotopes of CO_2 and CH_4 and trace species such as carbon monoxide (CO), hydrocarbons, and carbonyl sulfide (COS) can provide additional constraints for source attribution and diagnosing carbon cycle processes.

The original NACP planning documents (Wofsy and Harris, 2002; Denning et al., 2005) anticipated a backbone network of sustained atmospheric observations, including in situ surface and aircraft measurements along with ground based remote sensing of CO_2 and CH_4 (n.b. dedicated satellite CO_2 and CH_4 sensors were then in early design stages). The sampling density and frequency recommendations were specified to track regional CO_2 and CH_4 surface flux variations with resolution approximately 800 km x 800 km (roughly equivalent to the area of Texas or the Midwest Corn Belt). Surface sampling from tall broadcast towers (100-500m) was recommended to ensure regionally representative sampling, and aircraft vertical profiles were recommended with sufficient frequency to resolve synoptic scale weather systems and enable surface flux estimation with minimal dependence on atmospheric transport models. Traceability to WMO calibration scales was emphasized, with measurement compatibility better than 0.2 ppm for CO_2 and 5 ppb for CH_4 in accordance with recommendations for regional studies from the World Meteorological Organization's group on Carbon Dioxide, Other Greenhouse Gases and Related Measurement Techniques (see Crotwell et al., 2019 for current recommendations).

Major US observing systems now include NOAA's Global Greenhouse Gas Reference Network (GGGRN)[3], NSF's National Ecological Observatory Network (NEON), the NASA Orbiting Carbon Observatory (OCO) -2 and -3 missions, and the Total Column Carbon Observing Network (TCCON). The Canadian Greenhouse Gas Measurement Program maintained by Environment and Climate Change Canada (ECCC) has grown from 3 surface in situ sites in 2004 to 20 sites in 2022, with greatly improved coverage across the Arctic. Additional in situ surface and aircraft monitoring sites are still needed to address coverage gaps across North America, especially in the Southeast US, Northern Great Plains, the Ohio River Valley, the Desert Southwest, and Mexico. TCCON and OCO-2/3 measurements are linked to WMO calibration scales via ongoing comparisons with profiles from calibrated aircraft in situ analyzers (Wunch et al., 2010) and balloon-borne AirCore profile samplers that reach altitudes up to ~30 km (Karion et al., 2010).

Surface, aircraft, and satellite measurements provide complementary constraints for top-down estimates of emissions and removals of CO_2 and CH_4. Atmospheric signals of surface fluxes are largest within the planetary boundary layer, but confident interpretation of near-surface observations is hindered by poorly characterized errors in model boundary layer physics parameterizations. In contrast, flux estimates informed by total column measurements may be relatively insensitive to model boundary layer errors, and satellite sensors can potentially provide comprehensive coverage during daylight cloud-free conditions[3]. However, signatures of recent surface fluxes are diluted in the total column (frequently < 0.5 ppm) and are superposed on a large and highly variable background (Feng et al., 2019). Thus, even small biases in satellite retrievals can overwhelm recent surface flux signals (Rastogi et al., 2021).

Aircraft vertical profile measurements extending from the surface through the planetary boundary layer and well into the free troposphere (e.g. Sweeney et al. 2015) are especially useful for separating local and far-field influences and for diagnosing errors in simulated atmospheric transport that can lead to biased flux estimates, such as was one focus of the NASA Atmospheric Carbon and Transport (ACT-America) campaign (Davis et al., 2021; Figure 3.1.1). Understanding the impact of synoptic weather and convective cloud transport on this vertical mixing is also critical and requires weather-focused intensive observations (e.g. Davis et al, 2021; Wei et al., 2021). Commercial aircraft are a promising platform to greatly expand in situ vertical profile sampling, which has been limited by cost and complexity. NOAA recently partnered with Boeing and Alaska Airlines to demonstrate the feasibility of autonomous, high quality CO_2, CH_4, CO and H_2O measurements onboard their 737 MAX 9 ecoDemonstrator Aircraft. Commercial aircraft flying regional routes in North America typically serve 4-5 flights per day, so even a modest fleet of ~10 aircraft equipped with greenhouse gas sensors could provide thousands of profiles per month. Meanwhile, further development of data assimilation strategies and improved transport simulations are needed to optimally leverage the diverse constraints provided by current and emerging atmospheric CO_2 and CH_4 datasets.

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[3] Future satellite sensors using lasers as a light source may provide daytime and nighttime observations.

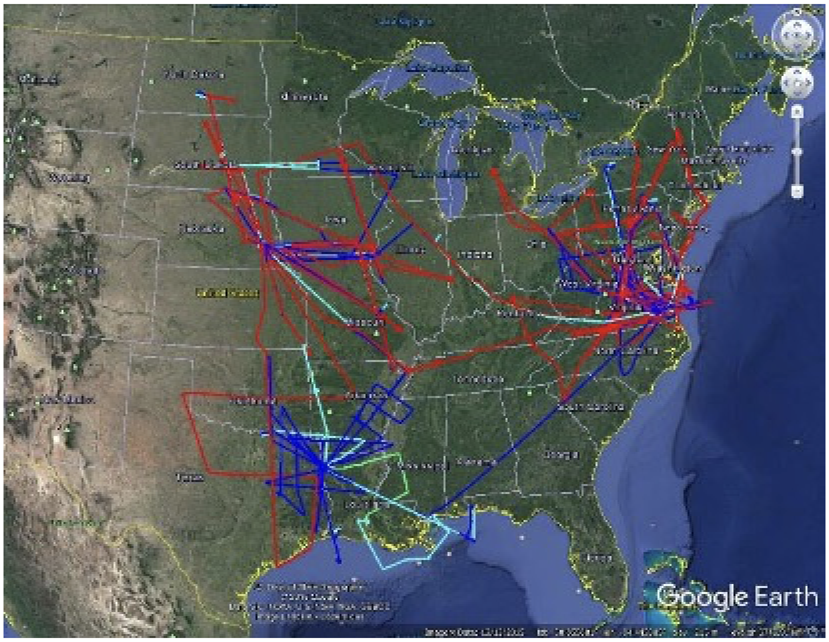


Figure 3.1.1. Improved atmospheric sampling is needed - as described in SOCCR2 Ch 8 and illustrated here with an example of the Spring 2018 campaign flight tracks from the NASA ACT-America campaign (Wei et al., 2021), an effort that included 121 research flights, 1,140 flight hours and 1,363 vertical profiles with two research aircraft. Expanded observations on commercial and research aircraft and satellites, on tall towers, with expanded gas tracers, and describing key characteristics of the atmosphere to improve transport simulation can together bring an advent of discovery and reduced uncertainty.

Anthropogenic Emissions

In the US, national total emissions and removals are reported by the EPA in its annual GHG Inventory. Anthropogenic emissions include a fossil component (e.g., emissions from extraction and use of fossil fuels), and a biological component (e.g., emissions from livestock and land use, including agriculture)[7]. In greenhouse gas inventories or emissions models of anthropogenic fluxes, fluxes are typically estimated by applying emission factors to activity data or by more complex process modeling. For example, the amount of fossil fuel consumption, and the carbon content of commonly used fuels are well studied and tracked. Emissions of greenhouse gases are often directly quantified using established methods and reported by individual operators to either state or federal entities, for example to EPA's Greenhouse Gas Reporting Program (GHGRP). Electricity generation facilities (power plants) also report emissions measured using Continuous Emissions Monitoring Systems (CEMS) to the EPA Clean Air Markets Division. EPA emissions inventories for UNFCCC reporting are intentionally focused on national-level fluxes over one-year intervals, and therefore do not typically provide the spatial and temporal resolutions needed for data assimilation and inverse modeling studies, nor for climate action planning and assessment. To complement the national-level GHG Inventory, and support inverse modeling, EPA has spatially disaggregated data in the national GHG Inventory in two related products: an annual state-level GHG Inventory, and a gridded CH_4 inventory (working with Harvard University, Maasakkers et al., 2016). Additional emissions models down-scale national-level estimates in space and time using proxy data (e.g., population, traffic counts, or night-lights) or models of temporal and spatial variability. Research products with high spatial resolution have been developed for CO_2 (e.g., Oda et al., 2018; Gurney et al., 2020) where the CO_2 products also represent temporal variability. Transitioning these research products to operational data services is necessary to meet stakeholder needs, to enable evaluation of inventories using atmospheric measurements, and to support data assimilation and inverse modeling studies.

Methods to use atmospheric measurements to quantify anthropogenic emissions are an active area of research. Prototype urban atmospheric greenhouse gas measurement networks have been deployed in several cities including three long-term NIST Urban Test Bed networks (Indianapolis, the Los Angeles air basin of California, and the US Northeast corridor[8]), enabling independent and high-accuracy evaluation of anthropogenic GHG emissions (e.g. Turnbull et al., 2019; Lauvaux et al., 2020; Sargent et al, 2018) as well as quantification of changes in emissions over time (e.g. Yadav et al., 2021; Turner et al., 2020). State agencies in California and New York have explored the potential of using atmospheric monitoring to estimate state-level emissions. Measurements of radiocarbon (^{14}C) in atmospheric CO_2 can provide independent estimates of fossil fuel emissions for comparison with inventories at urban to national scales (e.g. Basu et al. 2020), and sampling could be expanded to enable atmospheric tracking of regional and national emissions trends (NRC, 2010). New and upcoming satellite sensors have been optimized to map plumes from large point sources and urban areas are expected to provide data that can be used to assess and potentially improve emissions inventories, especially for CH_4. Private companies such as GHGSat and non-governmental organizations like the Environmental Defense Fund, which is developing MethaneSAT, and Carbon Mapper[9] have taken a leading role in developing new approaches for tracking anthropogenic emissions both from space and from tower- and aircaft-based observation (e.g. PermianMAP). Substantial progress has been made using atmospheric observations to quantify methane emissions from oil and gas infrastructure (e.g. Alvarez et al., 2018), and new sensing systems to locate and accurately quantify methane leaks at facility scales from the well pad to local distribution networks are emerging (Fox et al., 2019), including some that were supported by DOE's Advanced Research Projects Agency-Energy (ARPA-E) Methane Observation Networks with Innovative Technology to Obtain Reductions (MONITOR) program. Ongoing and targeted comparisons of top-down and bottom-up emissions estimates and diagnosis of discrepancies is expected to lead to improvements in both methods, including better characterization of uncertainties.

Terrestrial Ecosystem Stocks

Terrestrial ecosystem carbon stocks are estimated using inventory methods augmented by remote sensing data. The USDA Forest Service Forest Inventory and Analysis (FIA) Program provides information needed to assess the status and trends of forest land in the US and to project how forests are likely to change over the next 10-50 years. The National Forest Inventory (NFI) includes permanent sample plots distributed approximately every 2400 hectares across all land uses and ownerships in the US. The Forest Service is working with other US government agencies and research institutions to leverage all NFI data from annual and periodic inventories with auxiliary information (i.e., remotely sensed data) to improve the spatial and temporal resolution of estimates. Estimates of soil organic carbon stocks have relied on digital soil geographic databases such as the Soil Survey Geographic (SSURGO) Database and the US General Soil Map STATSGO2 that are produced by the USDA Natural Resources Conservation Service (NRCS). The USDA NRCS conducts the Natural Resources Inventory (NRI), a statistical survey of land use and natural resource conditions and trends on US non-Federal lands, including detailed data on soil properties. The USDA NRCS Soil Science Division conducted a separate Rapid Carbon Assessment (RaCA) project during 2010-2013 that was designed to provide a snapshot of the organic carbon content of soils across CONUS for different types of soils and land uses. No permanent soil carbon monitoring network has been established despite the potential for improved national inventories and to quantify the impacts of management practices. Efforts to sequester carbon in soils through land management practices would benefit from improved datasets, ideally aligned with a subset of the NRI points, to enable tracking of changes in soil organic carbon (SOC) resulting from land management practices or climate change.

Many components of vegetation and ecosystem structure can be measured using remote sensing technologies. Multi-spectral sensors such as Landsat can distinguish among land cover types such as forest, grassland, cropland, and urban areas with relatively high spatial resolution. Satellite data products have been developed for tracking burned area and other types of ecosystem disturbance. Hyperspectral sensors collect and transmit all wavelengths of radiation from visible to short wavelength infrared along with selected thermal-infrared wavelengths and can provide more detailed information about vegetation traits than is available from current satellite multispectral sensors. Lidar sensors measure reflected light from lasers to provide unique information on canopy height and other vegetation structural parameters. The Global Ecosystem Dynamics Investigation (GEDI) is a vegetation lidar on the International Space Station (ISS) that aims to quantify the distribution of aboveground carbon stored in vegetation, the effects of vegetation disturbance and recovery on carbon storage, the potential for existing and new/regrowing forests to sequester carbon in the future, and the spatial and temporal distribution of habitat structure and its influence on habitat quality and biodiversity. Synthetic Aperture Radar (SAR) sensors also provide information about vegetation structure but with the capability of wall-to-wall mapping and almost all weather and day/night imaging capability. The NASA-ISRO Synthetic Aperture Radar (NISAR) mission is a joint effort by NASA and the Indian Space Research Organization (ISRO) nominally scheduled for launch in 2024. The National Academies report, Thriving on Our Changing Planet, A Decadal Strategy for Earth Observation from

Space (2018) recommends a "Surface Biology and Geology" mission for NASA to provide additional detailed spaceborne measurements of vegetation traits, and candidate measurement approaches include hyperspectral imaging.

Terrestrial Ecosystem Fluxes and Drivers

Terrestrial ecosystem fluxes can be derived from changes in carbon stocks as indicated by inventories and other data products or by direct observations. The USDA Forest Service is responsible for compiling estimates of greenhouse gas emissions and removals from forest land, woodlands, urban trees in settlements, and harvested wood products as part of EPA's Inventory of US Greenhouse Gas Emissions and Sinks which is prepared each year as part of the US commitment to the UNFCCC. All forest and non-forest plots from the NFI are used in the compilation of annual carbon stock and stock change estimates for 5 ecosystem carbon pools – aboveground biomass (live trees and understory vegetation), belowground biomass (live trees and understory), dead wood (standing dead and downed dead wood), litter, and soil (mineral and organic) carbon – for forest land remaining forest land and land conversions to and from forest land.

In situ flux observations provide a critical benchmark for detecting trends and changes in the terrestrial carbon sink at the ecosystem scale, which is a primary evaluation method for Earth system models. Eddy covariance flux towers measure instantaneous fluxes of CO_2, H_2O, and energy and provide unique insight into crucial linkages between terrestrial ecosystem processes and climate-relevant responses. A key challenge in their application lies in upscaling and fusion with other data sources to generate regional to continental flux data products, but progress is being made in this area (Figure 3.1.2). Major US long-term observing systems include AmeriFlux (DOE), and the National Ecological Observatory Network (NEON, NSF), the Long Term Ecological Research sites (LTER, NSF), and smaller networks from USGS, USDA, and other agencies. Changes in SOC are generally based on assessments of stocks and some metric of turnover, residence, or transit time. The enriched atmospheric ^{14}C signal ("bomb C") has also been used to estimate SOC turnover timescales. Soil-to-atmosphere CO_2 flux (soil respiration or R_S) has been measured extensively and provides unique information about terrestrial carbon dynamics at fine temporal and spatial resolution.

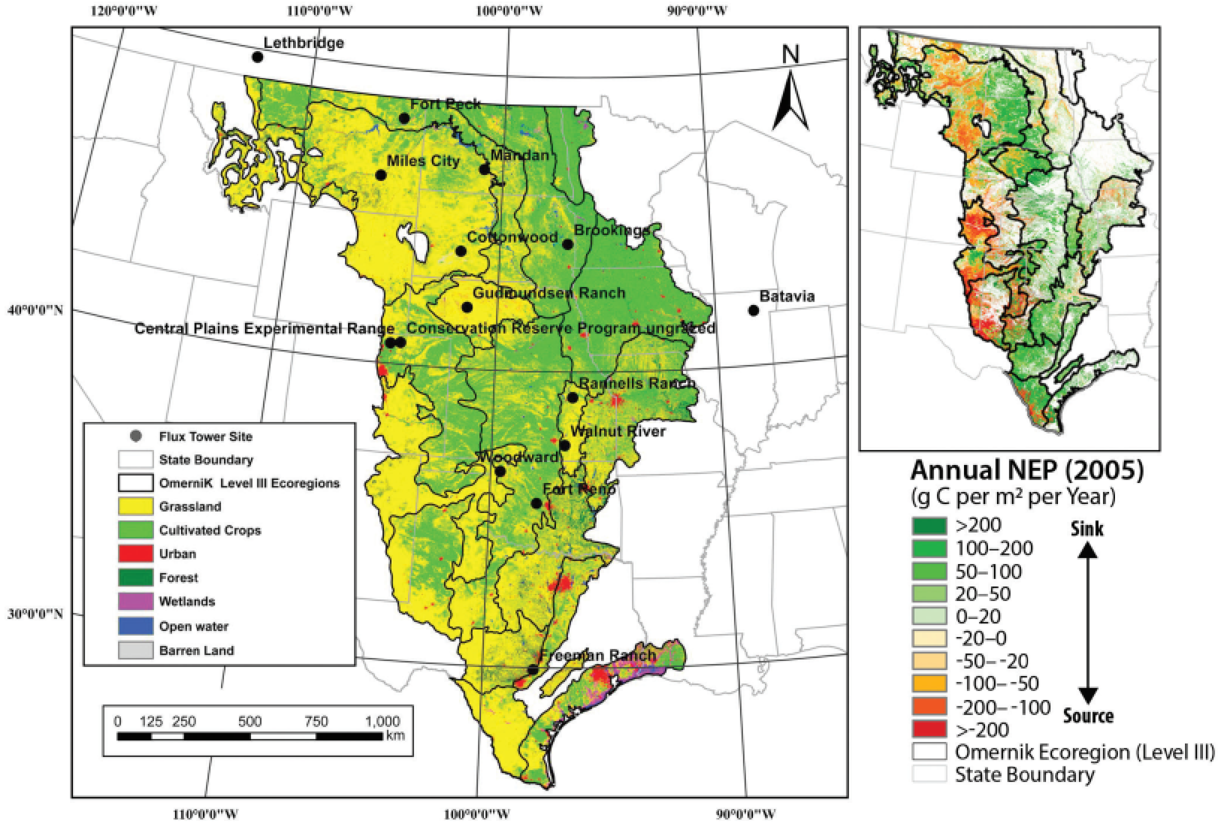


Figure 3.1.2. Upscaling techniques are needed to take point-based observations, such as flux tower measurements of net ecosystem productivity to create continuous maps as often needed by land managers. This image presents an example for the Great Plains Ecoregion, displaying land cover, grassland flux towers, and an upscaling estimate of net ecosystem production. No fire disturbance or land-cover change effects were included in the upscaling effort. [Figure reproduced from SOCCR2 Chapter 10 (Pendall et al. 2018)]

Satellite sensors can provide detailed “wall-to-wall” imagery used to infer key variables such as land cover, vegetation state, productivity, and disturbance history, including burned areas, insect mortality, and storm damage. Satellite optical imagery has provided sustained observations of simple metrics such as the normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI). Consistent time series are available from the Advanced Very High Resolution Radiometer (AVHRR) and the Moderate Resolution Imaging Spectrometer (MODIS) from 1981-present. The timeseries of imagery measurements will continue operationally through the 2040s via the Visible Infrared Imaging Radiometer Suite (VIIRS) instruments on the Joint Polar Satellite System (JPSS) series of satellites. JPSS is a collaborative program between NASA and NOAA. An NDVI time series has also been developed from the Landsat series, a collaboration between NASA and USGS. Satellite indices such as NDVI essentially detect the presence of live green vegetation and can be used to estimate the vegetation canopy extent and the fraction of photosynthetically active radiation absorbed by vegetation (fPAR) over broad spatial scales. Satellite optical imagery thus provides important spatial and temporal constraints on estimates of carbon uptake via gross and net primary production in process models. Satellite data products have been developed for tracking burned area and other types of ecosystem disturbance. The

Monitoring Trends in Burn Severity (MTBS) program aims to consistently map the burn severity and fire extent across the US from 1984 to present using Landsat data. The Global Fire Emissions Database combines satellite information from MODIS burned area maps with active fire data from VIIRS, the Tropical Rainfall Measuring Mission (TRMM), and the Along-Track Scanning Radiometer (ATSR) along with vegetation productivity to estimate gridded monthly burned area and fire emissions of carbon and other species.

Satellite imagery has been used to estimate terrestrial ecosystem fluxes such as the MODIS Gross Primary Productivity and Net Primary Productivity. A relatively recent innovation is the measurement of the emission of fluorescence from the chlorophyll of assimilating leaves; part of the energy absorbed by chlorophyll cannot be used for carbon fixation and is reemitted as fluorescence at longer wavelengths than the absorbed solar radiation. Global maps of solar-induced fluorescence (SiF) are available from GOSAT, GOME-2, OCO-2 and OCO-3. These are products of opportunity, since these sensors were not originally designed to measure chlorophyll fluorescence. The ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) measures the temperature of plants in order to better understand how much water plants need and how they respond to stress. ECOSTRESS was deployed to the ISS in July 2018 and addresses questions about how the terrestrial biosphere responds to changes in water availability and agricultural vulnerability to drought.

Satellite measurements of vegetation properties are complemented by ground based and aircraft remote sensing. For example, the PhenoCam network provides near-surface remote sensing of canopy phenology at many sites across the globe. Most sites are co-located with eddy covariance flux towers, and the data are being used to evaluate the implications of seasonal changes in canopy state for ecosystem function.

Inland Waters and Terrestrial Wetlands

Following SOCCR2, inland waters are defined here as open-water systems of lakes, reservoirs, non-tidal rivers, and streams. SOCCR2 identified large uncertainties on components of the North American budget related to transport of carbon through inland waters, wetlands, and estuaries. The lateral flux between land ecosystems and inland waters is an especially large term with uncertainty greater than 100%. Sedimentation and outgassing from inland waters and estuaries are also poorly constrained by the available data. Estimates of these components are complicated by high variability and the role of extreme events such as erosion associated with storms and flooding.

The quantification of the lateral flux of carbon from inland waters to estuarine systems is derived from long-term monitoring of water flow and decades of direct measurements of carbon concentration. The USGS National Water Information System as well as the EPA Water Quality Exchange (WQX, formerly STORage and RETrieval (STORET)) databases compile a wide range of data. For carbon accounting, a surface water network requires a minimum of seasonal or continuous data on water discharge, flow velocity, area of surface waters (from remote sensing), temperatures of surface waters and overlying air, pH, alkalinity, dissolved inorganic carbon (DIC) concentration, dissolved organic carbon (DOC) concentration (preferably with some measure of optical quality like specific ultraviolet absorbance (SUVA), partial pressure of CO_2 and CH_4 (pCO_2 and pCH_4, respectively). Most of the critical water quality parameters are currently measured at USGS stream water quality sites, and those of other networks (e.g. NEON, Consortium of Universities for the Advancement of Hydrologic Science (CUAHSI)) except direct measurements of pCH_4 and pCO_2. Particulate organic carbon (POC) concentrations are also lacking. Because emissions and burial are two of the largest uncertainties in SOCCR2 reporting, attention to these monitoring data are needed.

EPA scientists are collaborating with researchers at USGS and DOE to measure CO_2 and CH_4 emissions from 108 US reservoirs over the period 2020-2023. The Survey of Reservoir Greenhouse gas Emissions (SuRGE) will directly inform the emission estimates in the Inventory of US Greenhouse Gas Emissions and Sinks and will provide insight into the environmental factors that influence emission rates.

Future research needs to take advantage of developments in both large- and small-scale data acquisition and should attempt nested watershed studies across scales to understand the carbon cycling within inland water environments (Pekel et al., 2016). It is now possible to instrument inland water systems along the aquatic continuum from when water emerges from the terrestrial interface to when it is exported to the coast or large inland lakes. (Baehr and DeGrandpre, 2004, Bastviken, et al., 2015; Johnson et al., 2010). High-temporal datasets (Downing et al., 2012) are important for identifying the role that discrete, short-duration storm events play in carbon fluxes. Attention is needed to address continued loss of USGS gaging stations, as well as EPA lake assessments that are presently limited to every 5 years, which together yield spatial and temporal data that are insufficient for conducting robust national to continental flux estimates. Also, the inland water carbon cycle science community should learn from the efforts of organizations like the International Ocean Carbon Coordination Project to develop standard approaches and reference materials for study comparison and reproducibility.

The carbon density in wetlands is typically greater than terrestrial lands, and they are a source of CH_4, hence tracking changes in stocks and fluxes is particularly important for the NACP (Kolka et al. 2018). The carbon stocks and GHG emissions from wetlands are inextricably linked to hydrology. Accordingly, there is considerable intra- and inter-annual variation in emissions in response to variations in precipitation and groundwater. Long-term changes in hydrology caused by climate change or development can alter wetland functions, notably carbon cycling, resulting in significant increase in emissions. The uncertainties in GHG emissions from freshwater wetlands is high, due to the relative paucity of measurements compared to upland ecosystems. Although wetland restoration is often used to offset loss of wetlands from development, the uncertainties are great with respect to carbon sequestration and emissions.

The National Wetlands Inventory, conducted by the US Department of Interior, provides a periodic assessment of the extent and distribution of wetlands and open waters in the conterminous United States (CONUS). The most recent estimate of wetlands in the CONUS is 395,197 km^2 of terrestrial wetlands (USFWS 2011). Conversion of wetlands to other land uses has resulted in an approximately 50% reduction in the total wetland area. The recent rate of wetland loss has declined substantially, but losses continue to outpace gains (USFWS 2011). The US Environmental Protection Agency assessed the condition of wetlands in the US in 2011, and found 48% in good, 20% in fair and 32% in poor condition (US EPA, 2016). The degraded condition in 52% of the wetland resource suggests impairments to the carbon cycle, but this has not been affirmed.

While the importance of freshwater wetlands to the national carbon inventory is acknowledged (SOCCR2), work to reduce the uncertainties in estimates of C stocks and fluxes is needed. One of the issues in assessing C stocks in freshwater wetlands at the national scale is that the area is relatively small compared to other land resource areas. Accordingly, an explicit framework acknowledging the differences in basic soil type (mineral, organic soil) and vegetation (forest, non-forest) is warranted to improve the empirical basis for estimating stocks and fluxes, and to provide a coherent large-scale basis for model validation, and for calibration and validation of remote sensing technologies. Linking the exchange of carbon (e.g., DOC, DIC, dissolved CH_4) between uplands, wetlands and downstream water ways is also another major uncertainty, and one that is sensitive to changes within the watershed as well as alterations in hydrologic regime. Focused work on the hydrologic linkages could reduce uncertainties associated with hydrologic flux and provide an important foundation for testing airborne sensors for dissolved carbon fluxes.

Effective predictions of wetland carbon stocks and emissions are precluded due to both model limitations (Kolka et al. 2018) and the lack of a large-scale, dynamic database to support model testing and validation. The combination of a focused land-based monitoring network in conjunction with the development of airborne and space-based sensor technologies will provide much needed capabilities to improve wetland carbon assessments.

Coastal Margins

Coastal lands are notoriously difficult for satellite observations at scales that can be used to model fluxes, stocks or vulnerability. Further, coastal lands are highly dynamic in space and time, with compounded responses to both press (sea level rise, air temperature) and pulse (storm, impoundment, etc.) disturbances. Ground level data are essential for key drivers of carbon models, including plant phenologic and hydrologic variables associated with greenhouse gas emissions. A national scale community clearing house for coastal wetland data has begun (NSF's Coastal Carbon Research Coordination Network) and provides transparent data sharing for model development and statistical analysis.

The EPA's US Inventory of Greenhouse Gas Emissions and Sinks currently uses national scale data for coastal wetland reporting, and significant data gaps are identified by

Holmquist et al. (2018) to be related to methane emission factors, and fates of eroded carbon within the estuarine landscape. For example, the estimates within the Inventory include both tidal marsh and mangroves, but carbon stock changes in seagrass meadows are missing due to lack of data on areal extent and change over time. Challenges with water clarity in areas of seagrass make observations quite challenging. It is well documented that wetland loss continues but also that there is active building of marsh elevations and footprints, both progressive and transgressive. Methane, in particular, is poorly constrained for wetlands with annual salinity averages of less than half-strength seawater (<18 parts per thousand), which is likely more than 85% of tidal wetlands. Soil carbon erosion and soil carbon gain are spatially related (Herbert et al 2021) and that interdependency complicates estimates of where coastal carbon pools are redistributed. Models that can quantify both GHG emissions and lateral C transfers are limited, but using long-term and high frequency data from targeted research sites (e.g., Global Change Research Wetland (GCREW), AmeriFlux) in process-based models are pointing toward hydrologic drivers of both physical and biological drivers, both for gross primary productivity and ecosystem respiration pathways. Further, CONUS-scale products (e.g., Holmquist and Windham-Myers 2021) are increasingly available to support model runs and sensitivity testing for additional observational needs.

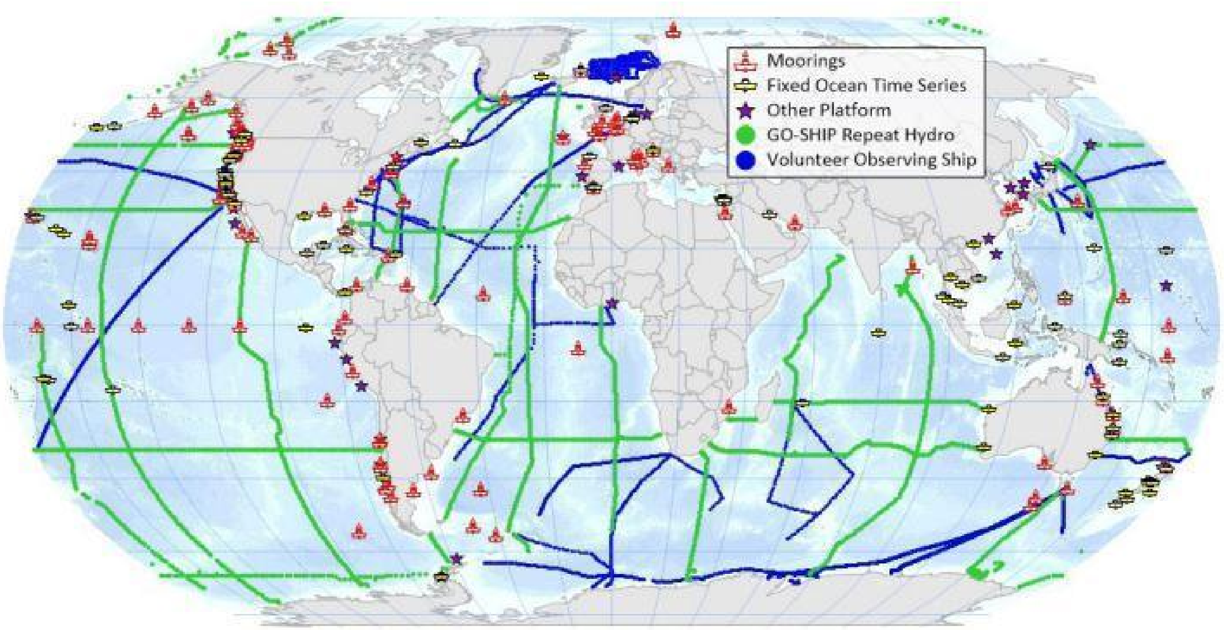


Figure 3.1.3. Present-day Global Ocean Acidification Observing Network, which is collaborative with the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) surveys, the Surface Ocean CO_2 Observing NETwork (SOCONET), the Ship of Opportunity Program (SOOP) volunteer observing ships, and the Ocean Sustained Interdisciplinary Time-series Environment observation System (Ocean-SITES), and other open ocean and coastal observing networks. [Figure reproduced from Chapter 2 the NOAA Ocean, Coastal, and Great Lakes Acidification Research Plan: 2020-2029, https://oceanacidification.noaa.gov/ResearchPlan2020; Figure 2.2 (Feely et al. 2020)]

Since 2010, NOAA's Ocean Acidification Program has operated an observing program supporting government and academic researchers responsible for quantifying carbon stocks and accumulation of anthropogenic carbon in coastal waters, as well as understanding current and likely future impacts of ocean acidification on marine ecosystems and resources (Jewett et al. 2020). Observations along all North American continental shelf regions—with partners from Mexico, Canada, and Indigenous Nations—include a combination of research cruises, time-series moorings, and underway measurements from ships and autonomous vehicles (Figure 3.1.3) as part of a comprehensive sampling scheme designed to cover relevant space and time scales (Figure 3.1.4). The combination of expanded observational coverage and increasingly sophisticated dynamic coupled physical-biogeochemical models have contributed to updated coastal CO_2 flux estimates (e.g., Fennel et al. 2018) and forecasts and projections of ocean warming, acidification, and hypoxia in North American coastal environments on daily, seasonal, and decadal time scales (see examples in Jewett et al. 2020).

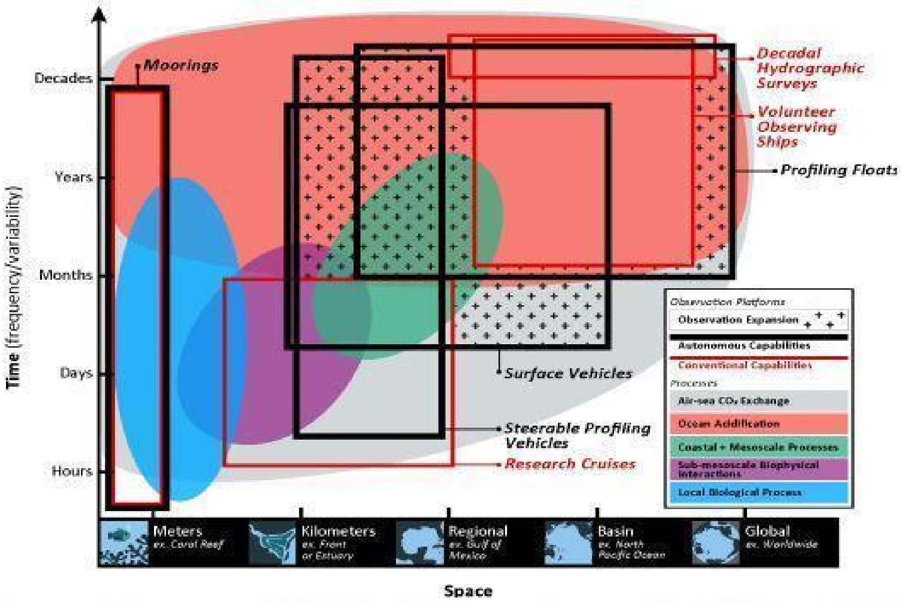


Figure 3.1.4. Diagram of observational capabilities for observing marine carbonate system processes over time and space. [Figure reproduced from the NOAA Ocean, Coastal, and Great Lakes Acidification Research Plan: 2020-2029, https://oceanacidification. noaa.gov/ResearchPlan2020; Figure 2.4 (Feely et al. 2020)]

National Ecological Observatory Network

The National Science Foundation's National Ecological Observatory Network (NEON) is a continental-scale observation facility designed to collect long-term open access ecological data to improve understanding of how US ecosystems are changing. Currently having 47 terrestrial and 37 freshwater aquatic sites spanning 20 ecoclimatic domains spread throughout the United States (Figure 3.1.5), NEON field-based measurements provide detailed information that characterizes local, site-level change. Complementing field data with airborne remote sensing data as well as existing satellite data capture supports extension to continental characterization of ecological processes with emphasis on key themes of biogeochemistry and ecohydrology.

Nearly all of the measurements conducted by NEON are of value for carbon cycle science. Those of greatest relevance include eddy covariance measurements of ecosystem-atmosphere carbon dioxide and methane exchanges, biomass and soil carbon stocks in terrestrial systems, and carbon and nutrient concentrations and transport in aquatic systems. Also essential are the ancillary measurements of environmental and other ecological conditions that accompany these carbon-focused quantities and that are essential for understanding the processes and mechanisms that control carbon dynamics. Despite its large size, involving major infrastructural investments with committed and coordinated operations, the endeavor still samples only a small fraction of each ecological domain, seeing just a portion of its diversity. The observatory is not designed to measure some of the factors influencing the contemporary carbon cycle such as effects of land use and management. Yet, acting in concert with many other observing systems and experimentation programs, together these efforts can depict how the carbon cycle of US ecosystems are changing today and can be expected to change in the future.

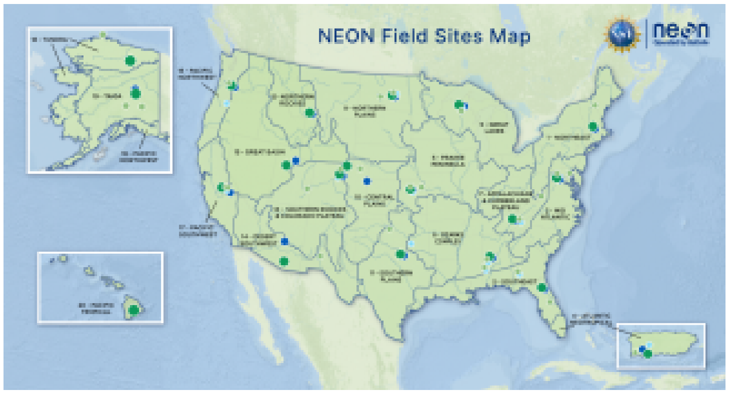


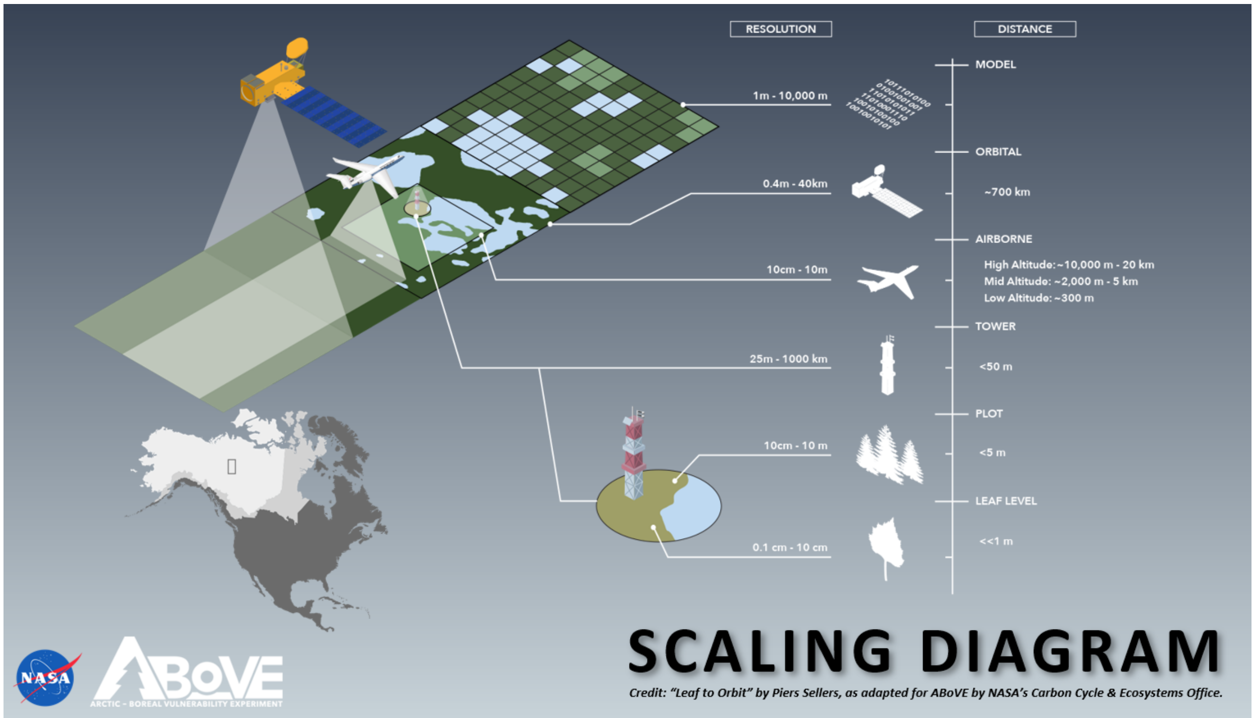
Figure 3.1.5. NEON field sites and ecoclimatic domains, taken from https://www.neonscience.org/field-sites/about-field-sites

Ancillary Measurements

A broad array of ancillary measurements are essential for interpreting, scaling, and predicting carbon cycle dynamics in space and time. They are too numerous to list exhaustively, but we mention a few as highlights. Climate and environmental conditions are fundamental controls on ecosystem carbon fluxes and stocks, including precipitation, temperature, humidity, solar radiation. Soil attributes are important controllers such as moisture status, depth to water table, pH, organic matter concentration, soil texture, and macronutrient (N, P, K) concentrations. Ecosystem-level vegetation abundance and species composition are important as well. Land use and disturbance history and contemporary management activities are of fundamental importance. Discharge, nutrient concentrations, water quality, and species composition and abundances throughout aquatic systems and adjacent riparian and wetland areas are essential. Baseline knowledge of these and other conditions as they vary through space and at daily, seasonal, and interannual timescales are required for conducting NACP science and for reaching the programs broader aims.

3.1.3 Intensive Measurements

Intensive measurements and focused sampling campaigns enable detailed process studies to support mechanistic modeling, to test new technologies and measurement strategies, to prototype data collection and analysis frameworks, and to quantify uncertainties of products and analysis derived from sustained observations. Intensive measurements can serve as a testbed for new sustained observations, e.g. to optimize the sampling strategy and to demonstrate the value of new technologies and emerging capabilities. Intensive sampling campaigns facilitate the development of integrated, multi-scalar, multi-platform and hierarchical observing systems (Figure 3.1.6), and are often leveraged to provide critical validation data for remotely sensed observations or other types of new data (e.g. ocean pCO_2 from biogeochemical Argo floats equipped with pH). Conversely, sustained observations provide spatial and temporal context for intensive studies to the extent that calibration and validation ensures that measurements are compatible. Design of intensive research campaigns involves strategic progression through developmental phases in planning, implementing, analyzing, and communicating science (Figure 3.1.7).



Credit: "Leaf to Orbit" by Piers Sellers, as adapted for ABoVE by NASA's Carbon Cycle & Ecosystems Office.

Figure 3.1.6. Integrated, multi-scalar, multi-platform observing systems require thoughtful design, including intensive experiments in areas most likely to be undergoing rapid change. Such a design is illustrated with this example from the NASA ABoVE program https://above.nasa.gov/materials.html.

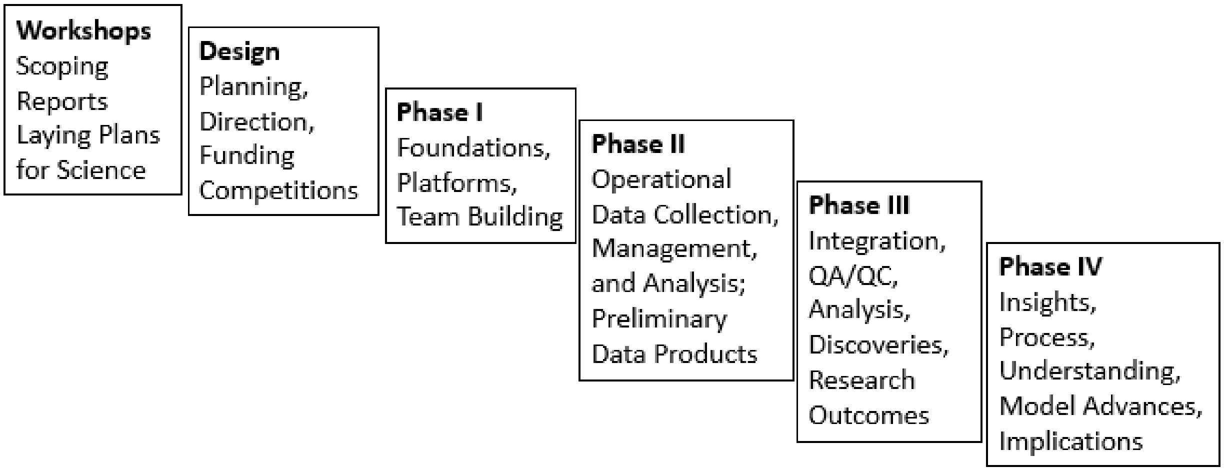


Figure 3.1.7. Strategic progression for research campaigns leading through developmental phases of planning, implementing, analyzing, and communicating science, adapted from the DOE NGEE-Tropics project (https://ngee-tropics.lbl.gov/about/our-project-2).

A series of coordinated multidisciplinary intensive experiments was anticipated to test NACP experimental concepts and to advance process understanding. One such experiment, the NACP Mid-Continent Intensive was selected from a multi-agency call for proposals, with the objective of developing robust methodology to reconcile top-down and bottom-up carbon flux estimates for a region with large fluxes due to agriculture and relatively simple terrain. Despite the success of that activity, there have been no subsequent multi-agency sponsored intensives explicitly focused on further developing top-down versus bottom-up methodology in the context of the NACP. However, many Agencies have supported intensive sampling programs that are aligned with and informed by NACP objectives. Here we provide examples of intensive experiments with strong links to NACP, noting that only a small subset of all relevant activities is captured here.

Errors in simulated atmospheric transport are a primary driver of uncertainty in top-down estimates of surface carbon fluxes. The NASA sponsored Atmospheric Carbon Transport - America (ACT-America) experiment included five airborne campaigns across three regions in the eastern United States and addressed three primary sources of uncertainty in estimating CO_2 and CH_4 sources and sinks from atmospheric measurements - transport error, prior flux uncertainty, and limited data density. The NSF-led Chequamegon Heterogeneous Ecosystem Energy-balance Study Enabled by a High-density Extensive Array of Detectors (CHEESEHEAD) was designed to investigate the role of atmospheric boundary-layer responses to scales of spatial heterogeneity in surface-atmosphere heat and water exchanges using a diverse suite of state of the science technology and models. CHEESEHEAD focused on the long-running tall tower measurement site in Park Falls, Wisconsin, that hosts AmeriFlux, NOAA GGGRN, and TCCON observations.

Arctic observations are extremely challenging due to the inaccessibility and remoteness of candidate sampling locations. Satellite observations that measure reflected sunlight are limited due to darkness for much of the year. SOCCR2 identified the following key uncertainties as to the future of carbon storage in Arctic and boreal regions: the extent to which plant community productivity will respond to elevated CO_2, whether landscapes will become wetter or drier in the future, the magnitude of winter fluxes, and the extent of the permafrost carbon feedback. Research programs have addressed the critical need for Arctic observations through intensive efforts such as NASA's Arctic Boreal Vulnerability Experiment (ABoVE), and DOE's Next Generation Ecosystem Experiment -Arctic. Intensive field-based sampling campaigns are often partnered with remote observations as well as geostatistical and computational modeling efforts to support upscaling of locally-detailed, process-oriented understanding such that behaviors can be described over whole landscapes (Figure 3.1.8).

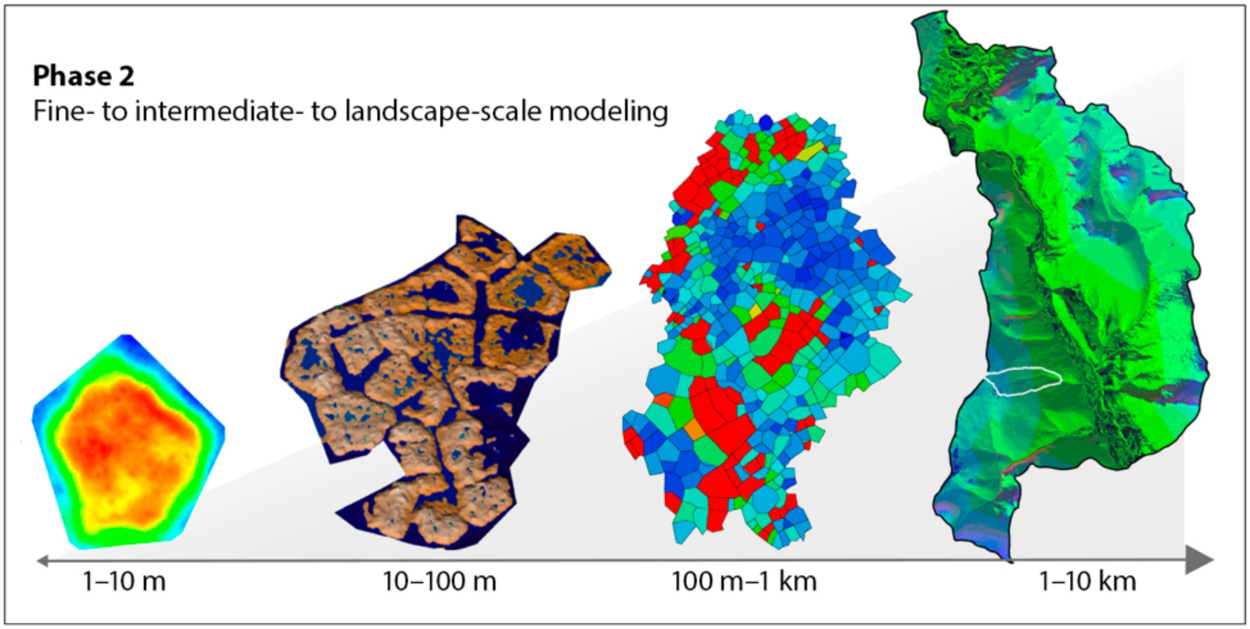


Figure 3.1.8. Research experiments are needed to improve predictive understanding of poorly understood processes analyzed in ways that are scalable, such as with the Next-Generation Ecosystem Experiments – Arctic (NGEE Arctic, https://ngee-arctic.ornl.gov/summary) project, which includes field plots and surveys with sampling designs to enable fine-, to intermediate-, to landscape-scale characterization of surface biogeochemistry and environmental biophysics, all of which are tied in to deliver process-based improvements within the land portion of an earth system model.

Urban experiments have emerged as a focal point for NACP agencies and researchers seeking to address decision-maker needs and to better understand drivers of emissions in cities as well as urban ecosystem fluxes. Short-term intensives are complemented by longer-term local measurements of urban metabolism such as NIST's Test Bed sites, as well as more extensive multi-agency/multi-partner GHG measurement programs in select US cities including Indianapolis, Salt Lake City, Los Angeles, Baltimore/Washington DC, Boston and San Francisco. Major sampling efforts are also underway in Mexico City and Toronto.

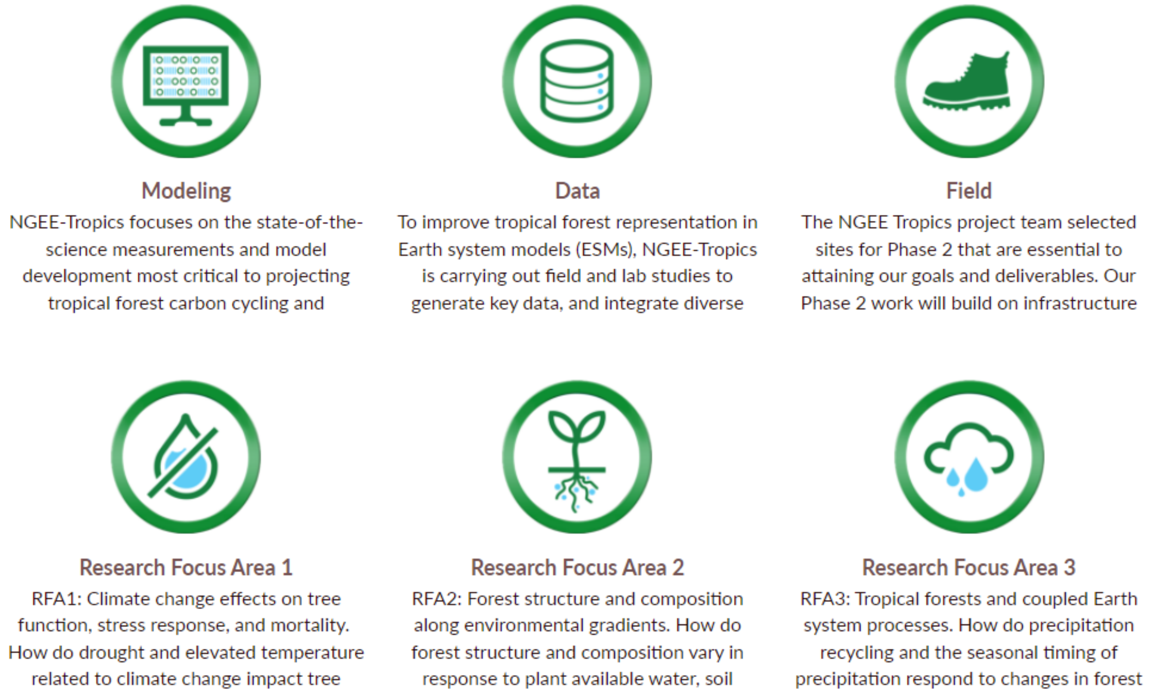
Urban ecosystems may differ substantially from surrounding regions and can either partially offset or enhance GHG emissions. Targeted aircraft sampling to measure atmospheric emissions, such as during the East Coast Outflow (ECO, Plant et al., 2019) and the follow-on ECO COVID-19 experiments during springs of 2018 and 2020, respectively, measured plumes downwind of urban centers along the US East Coast to estimate emissions of CO_2, CH_4, and CO. Notably, they found evidence of large fugitive CH_4 emissions and estimated total emissions more than double available bottom-up estimates for these cities. ECO COVID-19 revisited the region to assess the impact of coronavirus responses on air quality and greenhouse gas emissions.

Intensive atmospheric observations have also focused on quantifying emissions from oil and gas production and from coal mining. Flights downwind of major production regions have shown widely varying emissions (e.g. Peischl et al., 2018 Smith et al., 2015; Barkley et al., 2019a, b; Pétron et al., 2020) that repeatedly exceed inventory estimates (Alvarez et al., 2018)[10]. Aircraft measurements have also been used to quantify emissions from catastrophic leaks such as from the Deep Water Horizon oil spill (Ryerson et al., 2012) and Aliso Canyon (Conley et al., 2015). US EPA includes emissions from the Aliso Canyon event in the GHG Inventory and the most recent (2022) GHG Inventory incorporates satellite-derived estimates for three large well blowout events using emission estimates calculated in Pandey et al. (2019), Cusworth et al. (2021), and Maasakkers et al. 2022). Importantly, the US currently lacks a national rapid-response aircraft capability that can be quickly mobilized in the event of a disaster. State agencies such as the California Air Resources Board and non-governmental organizations such as the Environmental Defense Fund have played a key role in organizing and sponsoring intensive experiments. A growing number of private sector companies are emerging to meet government and stakeholder needs for reliable emissions estimation.

3.1.4 Manipulative Experiments

Manipulative experiments aid in assessing carbon cycle responses to individual driving factors as well as interactions among factors when deployed with a multi-factor design. Also, manipulative experiments are often used to study the response to very large changes in driving factors that exceed the bounds of what may currently be imposed. Furthermore, manipulative experiments support examination of underlying mechanisms that give rise to carbon cycle responses. Planning, designing and implementing manipulative experiments, and preparing scientific datasets, analyses and other deliverables requires a high level of organization and funding that supports large, collaborative teams of investigators extending well beyond the domain of an individual researcher. For illustration, we review a few recent examples that are providing insights into carbon cycle dynamics.

The Next-Generation Ecosystem Experiments–Tropics (NGEE-Tropics https://ngee-tropics.lbl.gov/), is a ten-year, multi-institutional project funded by the US Department of Energy (DOE), Office of Science, Office of Biological and Environmental Research (BER). NGEE-Tropics aims to fill the critical gaps in knowledge of tropical forest-climate system interactions. The overarching goal of NGEE-Tropics is to develop a predictive understanding of how tropical forest carbon balance and climate system feedbacks will respond to changing environmental drivers over the 21st Century. The project's approach involves manipulative field experiments and in situ observations, data analysis and computational modeling to address three focal research areas (Figure 3.1.9).



Modeling

NGEE-Tropics focuses on the state-of-the-science measurements and model development most critical to projecting tropical forest carbon cycling and

Data

To improve tropical forest representation in Earth system models (ESMs), NGEE-Tropics is carrying out field and lab studies to generate key data, and integrate diverse

Field

The NGEE Tropics project team selected sites for Phase 2 that are essential to attaining our goals and deliverables. Our Phase 2 work will build on infrastructure

Research Focus Area 1

RFA1: Climate change effects on tree function, stress response, and mortality. How do drought and elevated temperature related to climate change impact tree

Research Focus Area 2

RFA2: Forest structure and composition along environmental gradients. How do forest structure and composition vary in response to plant available water, soil

Research Focus Area 3

RFA3: Tropical forests and coupled Earth system processes. How do precipitation recycling and the seasonal timing of precipitation respond to changes in forest

Figure 3.1.9. The Next-Generation Ecosystem Experiments–Tropics (https://ngee-tropics.lbl.gov/) illustrates how manipulative experiments in the field can be combined with computational modeling and analysis to develop the understanding and predictive capabilities needed to advance carbon cycle science.

The Free-Air Carbon Dioxide Enrichment (FACE) Wood Decomposition Experiment offers another example. Established in 2011, it utilizes the unique isotopic signature of wood grown in two of the US-DOE FACE experimental sites to elucidate biogeochemical processes regulating wood decay on nine forest sites representing different biogeographic zones across the continental US (Trettin et al. 2021). The ongoing experiment is providing a unique opportunity to investigate the role of organisms (e.g., termites & beetles, fungi, bacteria) associated with wood decomposition and fluxes of wood-carbon into organisms, soil, water and atmosphere. Being continental in scale, it is helping to advance generalizable modeling of wood decomposition (Dai et al. 2021).

The Spruce and Peatland Responses Under Changing Environments (SPRUCE) experiment is the most extensive climate change manipulative experiment on the planet. At the USDA Forest Service Marcell Experimental Forest, high carbon peatland ecosystems are being heated above and belowground (five temperature treatments ranging from ambient to +9°C), as well as having elevated carbon dioxide treatments (ambient concentrations and

900 ppm). SPRUCE results indicate that even moderate warming changes peatlands from being long-term carbon sinks to sources of carbon dioxide and methane back to the atmosphere (Hanson et al. 2020) which exacerbates the potential for global warming.

The US National Science Foundation's Long Term Ecological Research (LTER) network has acted for decades as an important locus for manipulative experiments providing powerful insights into the ecological responses to global change. Site-based manipulative experiments have altered one or more of the following to study ecological responses over multiple years to even decades: rainfall, nutrients, temperature, sunlight, carbon dioxide concentration, disturbance, browsing/grazing, species composition and abundance or other conditions. While celebrating decades of success with this approach, to meet the scale and scope of global environmental changes, research scientists have called for a more coordinated approach to long-term experiments, with a network of multisite, multifactor experiments that are combined with ecological modeling (e.g. Knapp et al. 2012).

Finally, momentum toward testing carbon dioxide removal approaches and deploying them at large scale has rapidly accelerated in the last few years in industry, legislative, and non-governmental arenas (e.g., National Academies of Sciences, Engineering, and Medicine 2022). It will be incumbent upon this community of carbon cycle researchers to engage in experimental manipulations across ocean, terrestrial, and atmospheric sectors to ensure that efficacy and verification of the carbon budget implications and duration of carbon sequestration are rigorously assessed.

3.1.5 Key Priorities

- Establishment of an interagency National Carbon Monitoring System: Many prototype data products and services have been developed and successfully demonstrated under NACP and the NASA Carbon Monitoring System. A concerted effort is needed to transition products and services from the research realm to sustained operations with routine updates, while also supporting further development and improvements. Long-term support for the observational network must be secured and additional interagency coordination will be required with mechanisms to support ongoing input from stakeholders and the research community.

- Strategic investments to further develop and expand in situ measurements to address critical gaps in the current carbon observing system: Many key variables simply cannot be measured from space, while others can be measured but stability and resolution are inadequate. Validation data are needed that will serve a variety of emerging satellite measurement concepts and provide firm linkages across missions to enable confident interpretation of variability and long-term trends.

    - Expanded atmospheric monitoring:

        - Increased vertical profile measurements of atmospheric CO_2 and CH_4 to reduce uncertainties in top-down flux estimates, and to reliably identify and correct systematic errors in current and future satellite data products, and for diagnosing and improving atmospheric transport models. Commercial aircraft are a promising platform for cost-effective atmospheric sampling.
        - Expanded multi-species measurements, including radiocarbon of CO_2 to separately estimate biogenic and fossil fuel fluxes, along with other species such as CO, ethane and other hydrocarbons, carbonyl sulfide and stable isotopes of CO_2 and CH_4 to improve source attribution and advance process understanding.

    - A permanent soil carbon monitoring network is needed to improve national inventories and quantify the impacts of management practices. Efforts to sequester carbon in soils through land management practices would benefit from improved datasets to better quantify organic soil carbon stocks and to enable tracking of changes in SOC resulting from land management practices or climate change.

    - Coastal ecosystems including tidal freshwater wetlands are poorly represented at scales that influence both on-site processes (carbon burial) as well as transport across the landscape and coastal ocean (Land-Ocean Aquatic Continuum, LOAC). Leveraging field measurements is critical to supporting gridded products that can interact with remotely sensed inventories.

    - Estimates of CH_4 and CO_2 flux from freshwater wetlands are a source of major uncertainty in reporting greenhouse gas emissions. Accordingly, a programmatic initiative for in situ measurements in representative wetland types is warranted to develop a coherent database to support reporting, and modeling and remote sensing applications.

    - Longitudinally consistent measurements of biomass and ecosystem vegetation structure, repeated every 2 to 5 years and characterizing conditions at a 1 ha scale are needed from some combination of airborne and spaceborne lidar/radar remote sensing.

- Advances in both in situ and remote observational technology. Many in situ measurement programs remain limited by a lack of data that can be tied back to the cost and complexity of high-quality measurements GHGs and associated trace gases. Advances in ecosystem biomass and flux quantification are highly dependent on advances in remote sensing methods and data sets.

- Guidance from the science community to design an integrated and sustained carbon observing system including diverse ground-based, aircraft, ocean, and satellite observations with careful consideration of long-term costs, risks, and information content: This could be accomplished by an activity similar in scope and process to the Decadal Survey for Earth Science and Applications from Space.
    - The observing system should be sufficient to rapidly detect potential surprises in ecosystem and ocean fluxes that might result from tipping points or thresholds that are poorly represented or missing in current process models (e.g. faster than anticipated release of CO_2 and/or CH_4 from permafrost degradation)

    - The observing system should be capable of differentiating "background" ecosystem and ocean flux variability from uptake associated with carbon dioxide removal efforts deployed at large scale.

    - Rigorous Observing System Simulation Experiments (OSSEs) are needed to evaluate potential future combinations of diverse in situ and remote sensing observations and novel platforms. Particular attention is needed to define an optimal strategy for reliable detection and correction of systematic errors in models and in satellite data products.

    - Recommendations should include pathways for continuously incorporating new technologies while also ensuring continuity of long records.

- Routinely updated, high-resolution, national and global gridded estimates of anthropogenic emissions and ecosystem fluxes for CO_2 and CH_4 with well-characterized uncertainties and error covariances. Data products that accurately represent diurnal and day-to-day variability are needed to inform mitigation strategies and as inputs to atmospheric data assimilation systems.

    - Global inventory products such as ODIAC and EDGAR, are updated on a semi-regular basis, but are still managed largely by small research groups. US gridded national inventories have been developed under NACP (e.g. Vulcan, Anthropogenic Carbon Emissions System (ACES)). There is a continued need for a concerted effort to routinely produce gridded inventories for both gases that are updated along with the national reporting, and with the capability to trace and track emissions to sources and source processes.

    - Routinely updated, high spatial and temporal resolution terrestrial ecosystem flux estimates with realistic phenology, separate estimation of autotrophic and heterotrophic respiration and fire emissions, accurate representation of forest, grassland, agricultural, wetland, and urban ecosystem fluxes.

  - Maintenance and continued development of the observational resources to support improved inventories (e.g. satellite, ground-based and airborne remote sensing programs, AmeriFlux and NEON sites for ecosystem process understanding and modeling; NIST Test Bed cities and other efforts to track urban emissions, and oil and gas production monitoring programs).

- New coordinated intensive measurement and manipulative experiment activities to address key uncertainties identified in SOCCR2: A solicitation for whitepapers proposing new NACP intensive measurement campaigns is suggested. Two specific high priorities are noted here.

  - Intensive measurement programs to develop reliable protocols for comprehensive tracking carbon transport through inland waters, wetlands, and estuaries are needed to address large remaining uncertainties in the North American carbon budget and to reconcile top-down and bottom-up ecosystem flux estimates.
  - Manipulative experiments conducted in tidal freshwater marshes and forests at the ecosystem scale are needed to provide data for testing models and improving their performance for predicting how sea level rise, climate change, extreme events, and development may affect the carbon stocks and emissions in these critically important wetlands. Keystone sites representing major biomes in the Atlantic, Gulf and Pacific coasts, involving large interdisciplinary, multi-institutional teams are needed.

- A coordinated program for continuous monitoring of critical, large anthropogenic GHG sources that currently lack independent monitoring. Cities, major agricultural regions and oil and gas production basins are examples of large source regions whose emissions are relatively uncertain but whose location is well known but whose emissions are often quite uncertain. Independent and continuous atmospheric monitoring of emissions from these sources would provide the ability to track currently unconstrained anthropogenic emissions and support emissions mitigation efforts.

- Further development of methods to monitor emissions from energy and agricultural sources at the scale of individual producers or facilities.

  - This effort should include independent evaluation of commercial emissions monitoring technologies and evaluation of the data needed to inform inventory methods. GHG emissions must be evaluated on a site-level as new energy and agricultural technologies are developed (e.g. ‘green’ hydrogen productions; alternative animal agriculture management practices; carbon sequestration technologies), not after these technologies become widespread. Broader awareness of best practice methodologies for monitoring emissions at the scale of a feedlot or compressor station is needed, as well as continued innovations in these methods to keep up with technological developments in energy and agriculture.

- A rapid-response aircraft capability including state of the science multi-species in situ measurements and remote sensing is needed so that emissions resulting from catastrophic leaks or natural disasters can be rigorously investigated and quantified.

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Chapter 3.2: Integration, Synthesis and Assessment

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3.2.1 Introduction

The integration of diverse information, the synthesis of general insights, and the assessment of important implications are intrinsic to the North American Carbon Program.[4] The program requires a portfolio of multidisciplinary expertise from the natural sciences and socioeconomic disciplines. This expertise is applied across a broad span of spatial and temporal scales, including the long-term global context of interactions between carbon cycling and climate change. Measurements are needed from space-based and airborne platforms; from in situ sensors deployed in air-, ground-, and water-based instruments; and from laboratory analysis of samples representing the vast heterogeneity of materials and organisms that comprise the carbon cycle (e.g. Figure 3.1.6). Scientists acquire these measurements using combinations of remote data downloads, hands-on field expeditions, and advanced analytical procedures. Demographic and economic records are analyzed for features and trends that often involve innovative combinations of data. Mathematical analysis includes cutting-edge data assimilation and processing, advanced geostatistical methods, and computer simulations of carbon-cycle processes ranging from local and regional interactions to fully coupled Earth System models.

Since its inception, the NACP has focused on the mass balance of carbon as a central integrating concept and tool (e.g. see Figure 1.5). The physical mass balance of carbon serves as a quantitative constraint that can be applied to diverse observations and models. Mass balance assessments need to reconcile and resolve dissimilarities in the way different studies and different disciplines define and report carbon stores and fluxes. Attention to these dissimilarities is important not only for the integration of information across different scientific and socioeconomic disciplines, but also (and especially) for the consistent application of mass-balance constraints across economic sectors, governmental jurisdictions, and other “data domains'' that characterize data associated with human activities (sectors, regions, ecosystems, boundaries. While carbon mass balance calculations continue to be a critical integrating physical constraint, related concepts such as “carbon footprint” and the "carbon (or CO_2) budget" have extended to broader scientific and societal considerations regarding human interactions within the carbon cycle, and for which carbon is deeply embedded in the metabolism of society (Figure 3.2.1). Within this broader scope of interests, mass balance calculations are increasingly recognized as one tool among many integrating perspectives and needs.

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[4] In scientific planning, the terms “synthesis” and “assessment” are often confused. In this report, “synthesis” refers to the compilation and communication of information, while “assessment” refers to the evaluation of information quality, needs, and implications. For the NACP, both synthesis and assessment rely inherently on the integration of diverse information and perspectives.

Figure 3.2.1 Carbon is deeply embedded in societal functions of all kinds. 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. Managing associated carbon emissions from society requires holistic, systems-level thinking. It also requires social science research that involves people-centered analyses of energy use, consumption, governance, sociotechnical transitions, and social practices. By complementing physical science research, together these may inform carbon-relevant decision making and governance at multiple scales. [Figure reproduced from SOCCR2 Chapter 6 (Malone et al. 2018)]

The integration of diverse information is needed not only to address the multifaceted scientific goals of the NACP, but also to improve the communication of technical findings to non-specialists who need to understand the cycling of carbon in ways that are relevant to particular societal interests and concerns. The rapidly growing need for integrated public information poses significant challenges to the communication skills of NACP experts. At the same time, this challenge offers significant potential benefits for improvement of communication and understanding among the diverse academic and professional participants in the program.

The importance of integrated understanding and assessment to the North American Carbon Program is evident in the extent to which all of the sections of this NSIP describe plans for integration of observations, models, data analysis, and synthesis and assessment. The focus of this section is identifying broad needs for integration and assessment across the program as a whole. It first describes several general integration needs that are ongoing and emerging in current research and public interests. It then highlights particular challenges and difficulties in the implementation of integration and assessment activities. Finally, it suggests several specific activities that would help to address the integration and assessment needs of the NACP in the next few years.

3.2.2 Ongoing and emerging implementation needs

NACP requires near-term efforts to improve integration of data, models, and analyses of uncertainties; as well as pragmatic commitment to synthesis and assessment activities. The implementation needs described below are focused on issues that cut across diverse interests of the NACP community. Specific needs for data collection, modeling, and research are addressed in other sections of the NSIP.

1. Data integration

The importance of integrating diverse datasets is evident in the wide array of observational domains, ecosystems, and human activities represented by the topical chapters of the SOCCR2. The challenges of data integration are well illustrated by the difficulties of merging the diverse data sources that are necessary to characterize the transfers of carbon to and from the land surface. Information concerning energy commerce and technology is used to estimate trends in the distribution and nature of fossil fuel emissions. These estimates of emissions are combined with measurements of atmospheric chemistry and transport to infer (via inversion computations) the distribution of both fossil and generalized non-fossil CO_2 and CH_4 fluxes at the land surface. Inventories and surveys concerning land use and technology are used to estimate the more specific partitioning of land surface fluxes across areas ranging from cities to forests, croplands, and tribal lands (Figure 3.2.2).

Figure 3.2.2 Measuring and accounting for the carbon metabolism in society involves a suite of upstream, in situ, and downstream processes. Interactions are depicted between in-boundary (i.e. City Processes) or production-based urban carbon inventories and those that incorporate embedded or embodied carbon emissions either upstream or downstream. [Figure and caption reproduced from SOCCR2, Chapter 4 (Gurney et al. 2018)]

When applied to the overall mass balance of CO_2 exchange, these vastly different data sources have long yielded a stubborn divergence between inversions from atmospheric measurements (”top-down” estimates) and calculations from ground-based inventories and surveys (”bottom-up” estimates). The significance of this difference is difficult to resolve, due to uncertainties in the divergent estimates. The emerging availability of space-based CO_2 measurements may contribute to analysis of this problem by integration of frequent spectral measurements from multiple platforms and sensors. The synthesis provided by the SOCCR2 suggests possible progress from new understanding of the role played by lateral fluxes of carbon transported by water through and across soils, wetlands, and aquatic and coastal environments (Figure 1.5 and Figure 1.6). Datasets that characterize these lateral fluxes — which are not readily observable from space — are emerging as an important component of “bottom-up” mass-balance estimates. These additional data sources add to the challenge of data integration for many components of the NACP.

Emerging data integration needs:

a. Need for improved understanding of how carbon dynamics are linked among a suite of socioeconomic and environmental processes, mechanisms, flows, and networks in ways that can be traced and quantified with diverse kinds of data. ("My carbon is your carbon")
    i. Across domains (ecosystems, geographic systems, human systems)
    ii. Across temporal and spatial scales
    iii. A growing array of data sources and needs are emerging from groups and institutions concerned with developing and applying standardized protocols for assessment and monitoring of carbon storage and emissions of greenhouse gases (e.g., carbon management, mitigation protocols, economic- and social-sector-based, production-based vs. consumption-based, monitoring reporting and verification (MRV))
b. Rapid improvements in capabilities for data management to improve transparency, accessibility, and utility.

2. <u>Model integration</u>

Mathematical models are powerful integrative tools in carbon-cycle research, as they are constructed to organize many forms of knowledge within defined quantitative constraints. The integration of information from these models has become increasingly difficult, as their variety and complexity mirror the growing range of relevant knowledge and needs. Many of the NACP's fundamental advances and challenges are reflected in its evolving contributions to terrestrial carbon-cycle model development and analysis. Models are expanding to include more detailed portrayals of more diverse processes that affect carbon stores and fluxes. Examples include efforts to improve representations of vegetation demography and structure; soil hydrology and biology; impacts of wildfire, pests, and disease; and interactions among the biogeochemical cycles of carbon, water and nutrients.

One of the most important recent developments in carbon-cycle research is the incorporation of terrestrial carbon models as dynamic components embedded within Earth System models. This is a dramatic leap in both model integration and complexity, as the range of simulated interactions is extended to the fully coupled land-ocean-atmosphere-ice system at global scale. Global simulations are an essential prerequisite for understanding and anticipating many critical carbon-climate feedbacks in North America and other regions. Results from Earth System models provide an emerging list of important regional carbon-cycle impacts associated with global changes in atmospheric, oceanic, and cryospheric processes.

In carbon-cycle models at both global and regional scales, effects of human land use and emissions are typically prescribed as external model boundary conditions based on historical data or predictive scenarios. Innovations are ongoing to represent dynamic interactions affecting managed lands in ways that are more consistent with model treatments of natural ecosystems. These developments have potential to integrate modeling for research purposes with applications for the growing array of resource managers and others who are concerned about carbon cycling as a vital component of many land, water, and ecosystem resources.

Intercomparisons among models have provided understanding of differences and similarities among model results, with increasing emphasis on diagnosis of specific sources of differences and uncertainties (e.g., TransCom, MsTMIP, other MIPs, C-Lamp, iLAMB).

Emerging model integration needs:

1. Improved diagnostic and comparison methods and approaches to address increasing model complexity
2. Overarching issues:
    - Continuity and consistency across multiple spatial and temporal scales
    - Hindcasts: Can socio-economic models be subjected to hindcast testing? If not, this is a fundamental divergence in modeling "cultures" of physical vs socio-economic communities
    - Need for balance of interests in convergence of modeling efforts
        - "representative" or "average" may not be best for many specific applications
        - need for balance between innovations and consensus
        - Model hierarchies – e.g., space, time scales - but also need for simplified versions for access, transparency, ensembles and integrated assessments.

3. <u>Integration of uncertainty estimates and their implications</u>

The challenges of integrating data and models include a rapidly growing need for analyses and comparisons of uncertainties across the full range of NACP activities. Improved spatial and temporal data coverage has reduced uncertainties in estimates of carbon fluxes (e.g., combustion emissions) and stores (e.g., wetland soils). The analysis of mass balance constraints has highlighted the importance of comparing probability distributions across diverse datasets (e.g., top-down vs. bottom-up fluxes) and models (e.g., atmospheric inversions and dynamic vegetation models). Empirical statistical methods are increasingly important through their application to understanding uncertainties in data assimilation and model ensembles. Where fully quantitative measures of uncertainty are not feasible (e.g., in comparing results attributed to different model structures), estimates based on expert judgment remain an essential interpretive tool.

Emerging needs for integration of uncertainty analyses:
While improvements in uncertainty analysis are ongoing throughout virtually every aspect of the NACP, several overarching issues are emerging that require attention beyond the continuing refinement of uncertainty estimates for particular datasets and models.

    - Implementation of MRV standards across diverse data and models (improved and consistent probabilistic methods and analyses)
    - Trade-offs between increasing model complexity and measurable improvement of model reliability
    - Multi-scalar statistical metrics are needed, including analysis of error propagation across time and space.
    - Uncertainties in carbon fluxes and storage are viewed within a context of broader economic and social value/risk assessments

4. Synthesis and assessment

The recent publication of the Second State of the Carbon Cycle Report (SOCCR2; USGCRP 2018) has provided a comprehensive and authoritative synthesis and assessment of the state of knowledge regarding the carbon cycle in North America. The report was prepared under the auspices of the US Global Change Research Program and contributed to the congressionally mandated Fourth National Climate Assessment. Hundreds of scientists were involved as authors or technical reviewers, with final expert review by a committee of the National Academies of Science, Engineering, and Medicine. Broad input was also incorporated through a public review process, and through ongoing support and final approval by multiple Federal agencies. The information provided by the SOCCR2 is highly valued by both experts and non-experts. However, like the first SOCCR (CCSP 2007), such a massive endeavor cannot be repeated often due to the time and effort involved. While the SOCCR2 provides essential guidance for current scientific planning, one of the challenges facing the NACP is the need for more frequent assessment updates to provide information about ongoing new developments.

Topical syntheses and assessments have contributed valuable knowledge and understanding of research needs in areas of particular NACP interest. Syntheses and assessments focused on specific ecotypes (e.g., Coastal CARbon Synthesis (CCARS), Blue Carbon, urban carbon) and geographic areas (e.g., RECCAP, MCI, ABoVE) have demonstrated the value of such activities by not only summarizing current information for the broader scientific community, but also clarifying NACP research needs that often extend beyond narrow topical perspectives. Similarly, site-level monitoring and research activities are increasingly leveraged through coordinated programs that require standardized methods for broader synthesis, including increasing emphasis on links between ground-based and remotely sensed observations (e.g., FACE, NEON, ABoVE, NGEE-Arctic). Focused syntheses and assessments have addressed important methodological needs (e.g., scaling from discrete sample points to continuous landscapes, or, attributing carbon concentrations to source/sink fluxes and underlying process drivers) and modeling issues (e.g., the model inter-comparisons summarized above). Topical coordination has also drawn together communities of examining carbon-cycling in specific human systems (e.g., energy, urban, agriculture) (Figure 3.2.3) and managed land systems such as forestlands (Figure 3.2.4), yielding synthesis and assessment information of particular interest to actors in business, government and civil society (e.g., special issue of Earth's Future on urban carbon) .

Emerging synthesis and assessment needs:

- Community support for continuing system-level syntheses; e.g., wetlands, others topics as they develop
- Although SOCCR3 probably not needed in this NSIP time horizon (see above), need new formats for regular timely scientific community-based assessments
- Increasing need for improved public outreach that provides timely information in accessible formats

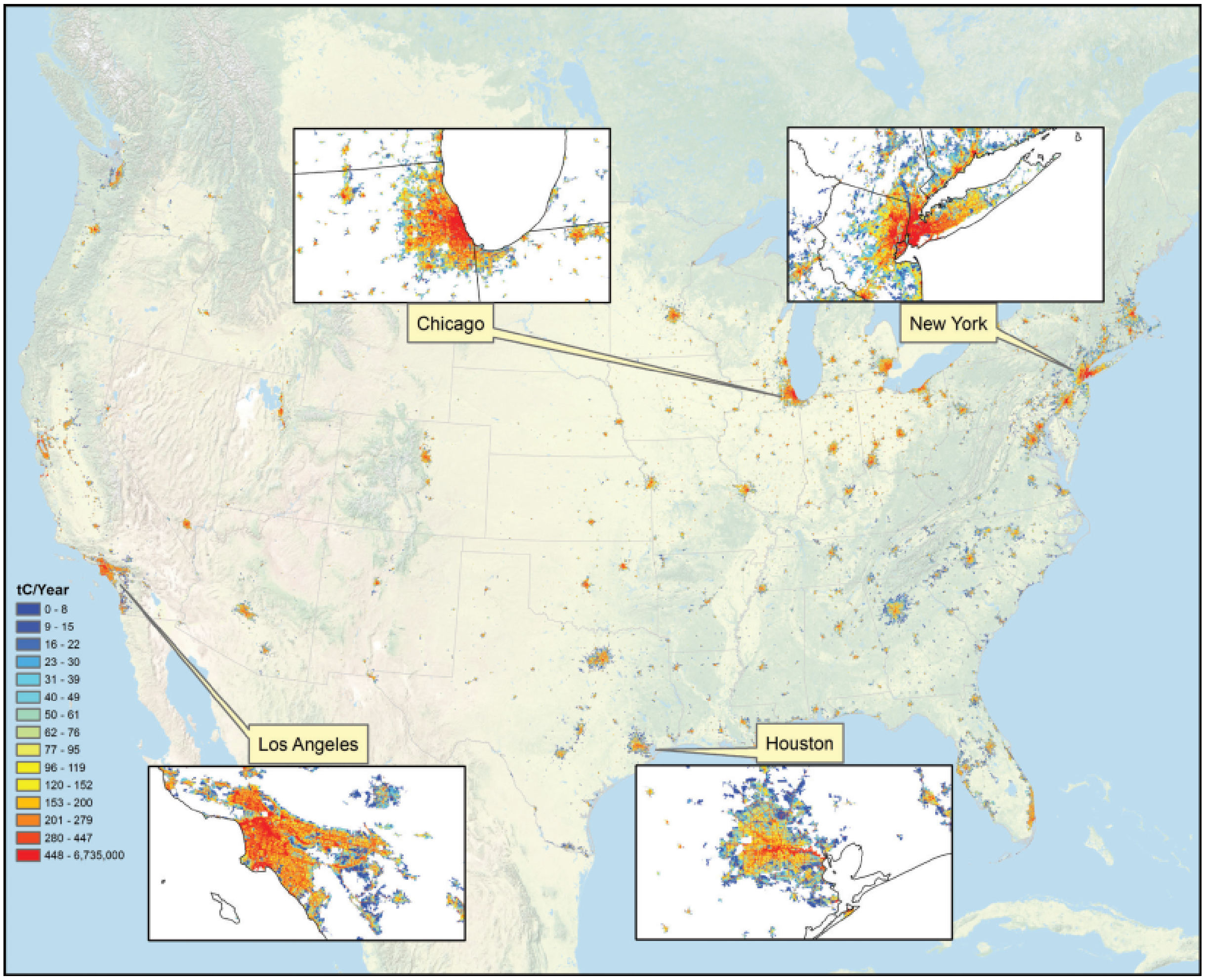

Figure 3.2.3. US Fossil Fuel Carbon Emissions, Highlighting Four Urban Areas. Urban and industrial areas are hotspots of carbon emissions, requiring design of observing systems capable of detecting trends in these focal areas, and also highlighting a key need for developing information systems that support policy making and management within urban domains. [Data source: Gurney et al., 2009; units in log 10 tons of carbon (t C) per year.] [Figure reproduced from SOCCR2, Chapter 4 (Gurney et al. 2018), Figure 4.4, p. 199.]

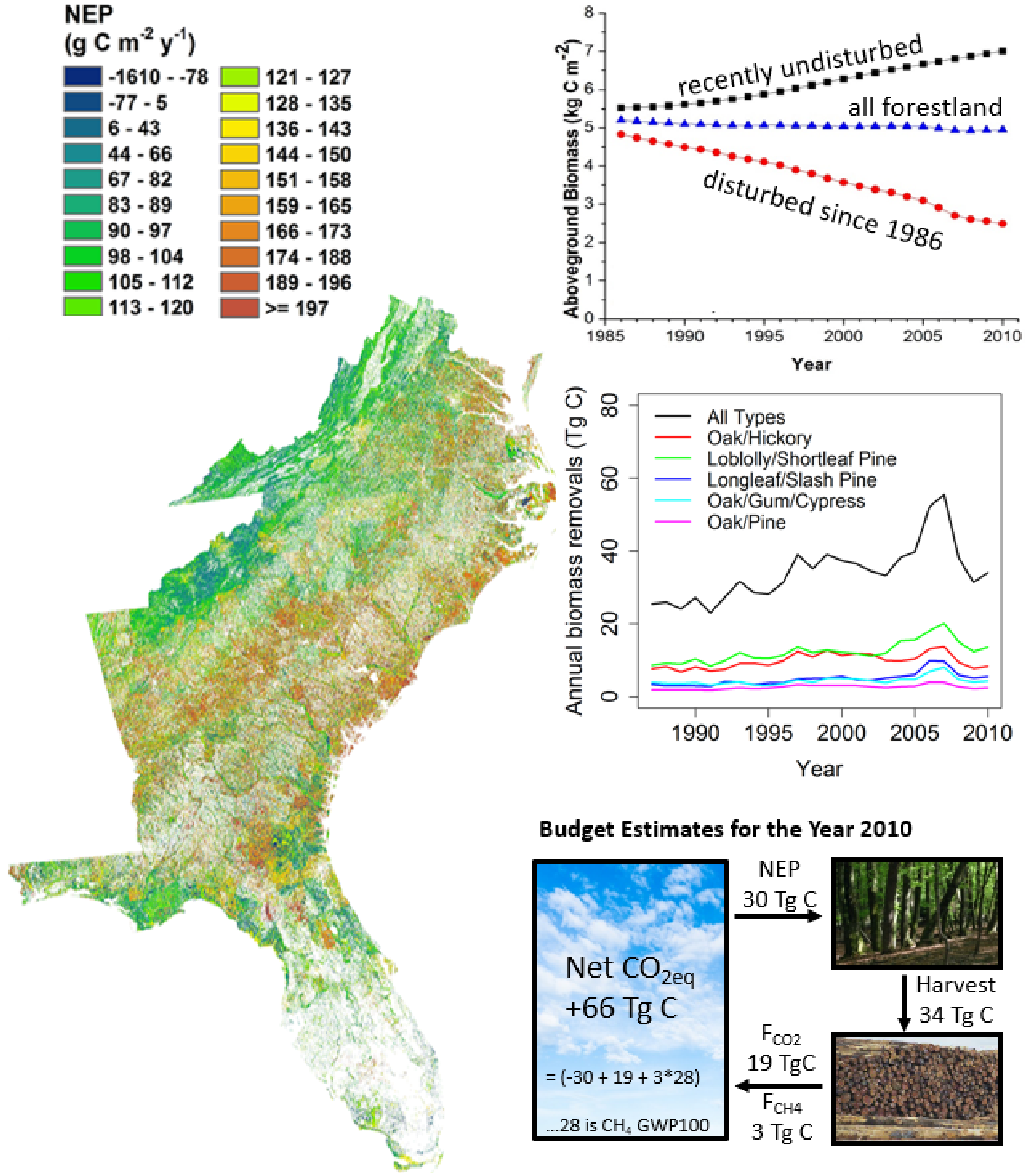

Figure 3.2.4. Carbon Dynamics of the Southeastern US Forest Sector Monitored with the Prototype National Forest Carbon Monitoring System. Synthesis of field inventory data, satellite remote sensing of disturbances, and computer modeling of ecosystem and wood product carbon flows and stocks portrays the effects of intensive forest management on net ecosystem productivity (NEP) within forestlands as well as the

net carbon dioxide equivalent fluxes among forests, wood products, and the atmosphere (budget estimates). [Figures and data sources from Gu et al. (2019)].

3.2.3 Implementation challenges

Needs and opportunities for integration, synthesis, and assessment follow the evolving science and information needs and interests. These program-wide activities are not necessarily at the "cutting edge" of process-based research, but they often provide essential translation to breakthrough constraints, and they generate important feedback concerning research and outreach needs and priorities. To maximize the benefits of integration, synthesis, and assessment, several challenges must be addressed. The changing and increasing need for timely and relevant information must be weighed against the exhaustive efforts and timelines of recent and past syntheses and assessments.

In particular, the information needs of actors in business, government and civil society are changing and becoming more urgent. Such actors are increasingly outspoken about the need for integrated synthesis and assessments that are relevant to policies and management decisions. Unfortunately, the exhaustive efforts often required for scientific integration, synthesis, and assessment do not necessarily extend ("translate") to timely and effective communication of the information needed by these communities of actors and decision makers. As these actors develop their own sources of information, methodologies and analyses, there is a growing risk of assessments, practices and standards that are tainted by self-interest or a lack of objectivity.

Integration, synthesis, and assessment activities are often difficult to develop and carry out. They require dedicated funding and community commitments that may limit resources available for more narrowly defined research. Integration, synthesis, and assessment require a very high "overhead" cost to develop and maintain the necessary collaborative and organizational arrangements. Recent and past endeavors have required long timelines from plans to products. These difficulties of time, effort, and overhead are disincentives for individual involvement, especially for younger scientists.

3.2.4 Proposed implementation activities

This plan cannot anticipate the full range of integrative opportunities and needs that may arise from the evolving science and decision-maker/actor concerns of the coming years. The intent of this section is to identify selected opportunities for targeted activities that address the needs and challenges summarized above. We emphasize that the activities proposed below, and other emerging integrative endeavors, will require attention not only to the proposed topics, but also to the inherent logistical difficulties and disincentives described above.

1. <u>Integration of observational data and synthesis for public access and understanding</u>

Public access to observational carbon data is expanding with the implementation of new standards and protocols for data management, documentation, and release. However, public understanding of these observations requires focused efforts to integrate and synthesize the datasets as they become available. An excellent example is the NOAA Earth System Research Laboratories (ESRL) CarbonTracker program (CT2019, Jacobson et al. 2020), an ongoing contribution to the NACP. This effort provides estimates of temporal and spatial variations in global and North American CO_2 fluxes by integrating a global network of atmospheric CO_2 observations with data and models of emissions, atmospheric transport, ecosystem fluxes, and ocean surface exchange. The program offers a powerful example of integrating multiple models and datasets with ensemble assimilation methods that support transparency and statistical analysis of uncertainties.

While CarbonTracker demonstrates the value of calculating atmospheric fluxes by inversion from atmospheric data, public interest extends to a broader range of carbon fluxes and stocks. There is a growing need for integration and synthesis that includes more diverse observations of ecosystems, soils, aquatic and marine environments, and human activities. Given the exhaustive time and effort required for the comprehensive SOCCR reports, new efforts are required to provide more regular and timely updates utilizing ongoing observations. For example, atmospheric inversions might be integrated with other data products to provide annual summaries of North American carbon fluxes and stocks. The value of such summaries is demonstrated by the wide public interest in the global carbon budgets released annually by the Global Carbon Project (GCP), an effort that involves contributions from the NACP community (Friedlingstein et al. 2022). Like CarbonTracker and the GCP syntheses, a new synthesis activity for North America would require full documentation and transparency, thorough analysis of uncertainties, and rigorous peer review. This new effort would be less demanding than a SOCCR-like compendium, but more demanding than a simple compilation of datasets and their separate statistical characteristics. To enable public understanding of diverse and sometimes divergent datasets, the effort will need to address (but not necessarily resolve) some of the data integration challenges described above.

2. Integration of methods to quantify uncertainties and their implications

Improved estimates of carbon-cycle uncertainties are needed by both scientists and actors in business, government and civil society. In addition to the refinement of uncertainty estimates for individual datasets and models, broader analyses are needed to address the complex uncertainties that arise in the integration of diverse datasets and models. We suggest the formation of a focused community of interest within the NACP to provide a venue for sharing and advancing the integrated analysis of uncertainties. This new effort should be guided by community interests, but potential directions might include:

- Identify critical factors limiting the reduction of uncertainties in analyses based on data/model integration. For example, ensemble sensitivity testing might be used to determine the extent to which uncertainties in atmospheric inversion calculations could be reduced by improved GHG monitoring or improved transport monitoring. Similarly, diverse soil datasets and models might be integrated to provide insights concerning opportunities and limits in reducing uncertainties in soil fluxes and stores.

- Improve statistical methods for model inter-comparison and diagnosis to address the challenges of increasing model complexity. For example, statistical tools and metrics might be developed to evaluate changes in uncertainties, and corresponding information gains and losses, associated with the introduction of new complexities in model components or structures. Conversely, statistical methods might be used to construct empirical reduced-complexity parameterizations that could be used to boost the efficiency of model ensembles.

- Improve program-wide consistency and application of probabilistic methods and analyses. The NACP research community faces many shared difficulties in efforts to improve quantification and understanding of uncertainties across diverse systems. Significant improvements are needed in the joint application of uncertainty estimates for fluxes derived from fundamentally different datasets. A conspicuous example is the ongoing effort to resolve differences in atmospheric CO_2 budgets calculated top-down and bottom-up datasets and models. Although convergence is suggested by the overlap of top-down and bottom-up ranges of uncertainty, a more challenging analysis is to estimate the joint probability distribution of the budget based on both datasets. This analysis would require determination of covariances and autocorrelation, and elucidation of underlying differences in data and model properties that might significantly augment our understanding of the CO_2 budget. Analysis of joint probabilities could contribute better understanding of uncertainties in many applications based on combined use of diverse datasets. A particularly important and challenging need is for improved integration between estimates of uncertainties associated with physical processes and those associated with effects of human activities.

- Improve quantification and understanding of uncertainties across spatial and temporal scales. This is a long-standing issue for NACP and for many other efforts that require consistent constraints (such as conservation of mass) across diverse scales. There is a robust body of statistical analysis and methodologies that could be more fully applied to NACP in such areas as comparison of diagnostic statistics vs prognostic (extrapolation) probabilities based on observational datasets; integration of MRV standards/protocols across spatial scales; quantification of uncertainties across predictive timescales (alternatives to model ensembles, and/or ways to optimize them); and improved understanding of joint spatial and temporal variabilities and uncertainties.

3. Integrated studies of interactions between carbon and water cycling
   Many important contributions to the NACP have developed from research themes that have been identified periodically for particular focus. Interactions between the cycling of carbon and water have always held implicit importance for the NACP, but recent and ongoing research have made this topic an appropriate target for more focused thematic attention. A major finding of the SOCCR2 was the potential importance of water-borne carbon transport in resolving divergent CO_2 budget estimates. This conclusion invites further scrutiny of many processes that control the interactive transport of water and carbon across the land surface and through soils, the unsaturated zone, groundwater, streams, rivers, and lakes. New interactions and collaborations are underway among carbon scientists, hydrologists, ecologists, and others. These collaborations include renewed attention to long-standing issues such as the interactions between soil moisture and heterotrophic respiration, between evapotranspiration and CO_2 fertilization, and between carbon and sediment burial in wetlands. Emerging research on these topics would be strongly leveraged by a new NACP thematic focus on interactions between carbon and water.

4. Integrated carbon accounting for science and for management/policy applications
   NACP research quantifies carbon stocks and fluxes to understand their cycling in and among the atmosphere, ecosystems, soils, and aquatic and marine environments. At the same time, carbon accounting methods and protocols are receiving increased attention and development for management and policy applications, particularly with accelerating interest in deploying carbon dioxide removal. The carbon-cycle research community and the carbon-accounting community would both benefit from stronger mutual communication and collaboration. Although divergence among methodologies and definitions is necessary to address different interests, both communities are ultimately concerned with the same carbon. (“My carbon is your carbon.”) Consistent estimates using divergent methods and data may provide measures of reliability. Conversely, divergent estimates may lead to unnecessary confusion, particularly where estimates of carbon fluxes and stocks are needed for management and policy decisions.

Improved communication and collaboration are most successful in areas of readily defined interest to both communities. Examples include resources and economic sectors that coincide with major ecosystems (forests, wetlands, agriculture), emissions (fossil fuels, energy, transportation), or geographic areas (urban, coastal). While scientist interactions with actors in business, government and civil society are generally expanding in these and other areas, broader communication is required for integration, synthesis, and assessment beyond specific areas of common interest. For example, scientist–user-community co-development is needed to establish metrics of potential CO_2 and CH_4 mitigation that are minimally dependent on particular models or global emission pathways and are presented in ways that make sense to both communities. Similar co-development is needed to improve the treatment of carbon cycling in scenario-based simulations such as integrated assessment models.

Important interests of both scientists and societal actors are converging in the integration of uncertainty analyses and probabilistic prognostic calculations. Scientific advances in applying geostatistical methods and ensemble simulations are contributing to significant improvements in estimating complex uncertainties associated with the integration of diverse data and models across multiple spatial and temporal scales. Similarly, societal actors are increasingly aware of the need for probabilistic assessments of carbon-cycle response to potential management and policy decisions. Overlapping scientist–user-community interests are evident in the attention of both communities to issues such as mitigation programs and protocols (e.g., REDD+, Trillion Trees) and inter-comparisons among carbon-cycle model simulations of scenarios for past and potential future emissions. Broadly integrated perspectives are expanding to recognize the importance of carbon in assessment of the value and availability of diverse natural resources such as water and ecosystem services. In this context, evaluations of carbon storage can be guided by long-established practices in natural resource assessment, including user-community contributions to methodology development, periodic inventories, and probabilistic estimates using Monte Carlo ensembles. The NACP community is uniquely qualified to explore the challenges of carbon storage resource assessment. This endeavor demands the full interactive engagement of NACP scientists and actors in business, government and civil society. Carbon storage cannot be managed in isolation from interactions with other natural resources.

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Chapter 3.3: Process and Attribution Studies to Uncover Mechanistic Responses of the Carbon Cycle to Natural and Anthropogenic Influences

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Quantitative understanding of the mechanisms and processes that govern the carbon cycle is important for diagnosing and predicting how the carbon cycle responds to natural and anthropogenic forcings. The carbon cycle of North America is experiencing forcings and perturbations from a wide range of natural and anthropogenic factors, particularly socioeconomic activities related to energy, transportation, industry, commerce, agriculture, construction, resource extraction, and urbanization. These factors are altering atmospheric composition, climate, extreme weather, and nutrient availability, as well as imposing direct disturbances to ecosystems. All of these factors can have interactive effects requiring system-level thinking (Figure 3.3.1). Understanding carbon cycle responses to these drivers and activities, across human, terrestrial, aquatic, and oceanic carbon cycle systems is incomplete and requires further study.

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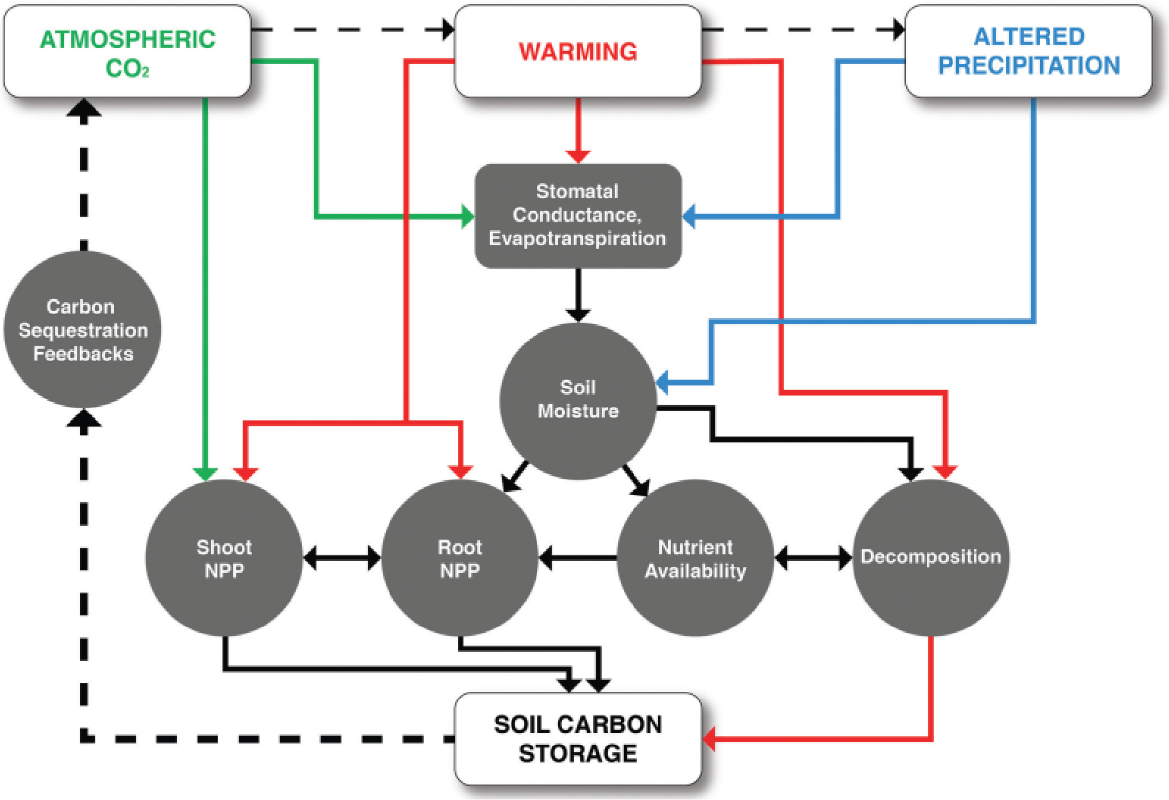

Figure 3.3.1. Example of Interacting Effects of Multiple Factors Influencing Carbon Dynamics in Grasslands. Systems approaches are needed to diagram and diagnose the separate, combined, and interactive effects of multiple drivers. [Figure reproduced from SOCCR2, Chapter 10 (Pendall et al., 2018), Figure 10.5, p. 411.]

Process and attribution studies are critical for addressing the goals of the NACP. Such studies reveal the contributions that individual processes make in driving today's sources and sinks of carbon. Process studies identify the importance of different drivers of the carbon cycle at regional to global scales, while attribution studies identify how distinct and interacting processes give rise to collective carbon cycle dynamics. Together, they advance understanding and enable skillful predictions of how changes in these forcings will alter the future state of the carbon cycle and its interactions with other components of the Earth System.

A complementary suite of methods is required to attribute carbon dynamics and reveal underlying processes, including the following:

- Process-oriented analyses of carbon cycle observations are needed to develop mechanistic understanding of carbon cycle responses to drivers, and to improve diagnostic and prognostic models of the carbon cycle.

- Manipulative experiments are needed to provide insights into carbon cycle responses to specific drivers and interactions among drivers, and to investigate how the carbon cycle will function in altered environmental and socioeconomic conditions in the future.

- Integrated field campaigns are needed to work across disparate observing networks, measurement systems, and experiments to advance broader and deeper understanding from synergistic study.
- Synthesis activities utilizing existing observational and experimental networks are needed to evaluate larger patterns of carbon cycle behavior.
- Long-term observations are required to examine carbon cycle responses to punctuated disturbances, to interannual variability in climate and human activities, and to decadal scale trends in diverse drivers.
- Scaling studies are needed to translate local, discrete measurements to larger spatial and temporal scales and to assess the integrated effects of carbon cycle drivers.
- Model-data integration and model intercomparison activities are needed to test models, identify gaps in process understanding, and bridge from process understanding to predictive capability.

With this backdrop of motivation, and general description of methods, the following subsections provide more specific guidance on research implementation priorities for developing process-understanding of the carbon cycle.

3.3.1 Responses of terrestrial ecosystems carbon cycling to changes in atmospheric CO_2, tropospheric O_3, N deposition, and climate

Many unknowns remain regarding how terrestrial ecosystems respond to changes in atmospheric composition and climate (Keenan & Williams 2018). The effect of rising atmospheric CO_2 on plant- to ecosystem-scale photosynthesis and carbon stocks in biomass, litter, and soils remain poorly understood, as well as the relations of those effects to nutrient dynamics as limiting or interactive controls. The lack of understanding is highlighted by long-term studies, which continue to yield variable results and conclusions given the complexity of the problem. There remains insufficient understanding of how the carbon cycle responds, over various timescales, to: (1) climate-related extremes (e.g. heat waves, frosts, droughts, floods, fires), (2) interacting global change drivers (e.g. CO_2, atmospheric N deposition, ozone, temperature, precipitation, and soil moisture forcings), (3) the magnitude and timing of permafrost degradation; (4) shifts in light quantity and quality from diffuse/direct illumination; and (5) shifts in biodiversity, species distributions and community composition.

In addition to advancing understanding of individual processes and site-level responses, research is needed to develop a more integrated and holistic understanding of carbon cycle behavior at the Earth System scale. This requires the use of ecosystem models informed by experiments in key regions, merged with atmospheric inverse modeling, remote sensing constellations and distributed sensor networks. Regions where soil or vegetation carbon stocks may be particularly vulnerable to environmental change include boreal forest and tundra ecosystems (inclusive of various states of permafrost), which have high carbon stocks and wide-ranging albedo, and are particularly disturbance-prone in a changing environment; tropical forests, which have high productivity, and a potentially high response to CO_2 fertilization; peatlands, which store large amounts of carbon and are frequently drained for anthropogenic means; and drylands, which contribute much of the world's productivity and food, and are likely sensitive to rising atmospheric CO_2 due to the implied higher water use efficiency while also being particularly vulnerable to warming and decreased humidity.

Observational and experimental studies play critical complementary roles in informing our understanding of ecosystem responses to global change. Long-term observations are essential to identify trends, characterize the historic range of variability, and generate hypotheses. Experiments are of fundamental importance for isolating processes and testing mechanisms, and pushing systems past tipping points that have not historically been exceeded. Also, we note the critical importance and great value of networked observational approaches, which are more easily standardized and synthesized across sites and networks, e.g. AmeriFlux, NEON, LTER and national forest inventory programs. Experimental protocols are difficult to standardize across different ecosystem types, and arguably a high degree of standardization is not realistic or even desirable, as the important questions and relevant mechanisms are undoubtedly different among diverse ecosystems. Thus, to maximize the return on investment, costly multi-factor global change and Free-Air CO_2 Enrichment Experiments (FACE) experiments conducted at the ecosystem scale should target the high-priority, ecosystem-specific research questions highlighted above. For example, the SPRUCE (Spruce and Peatlands Responses Under Changing Environments) experiment targets high carbon peatland ecosystems. Replication within a given ecosystem type (broadly defined) is essential to ensure the generality of results. Finally, although not as comprehensive in scope, focused observational networks (e.g. PhenoCam) and coordinated, grass-roots experimental efforts (e.g. Detrital Input and Removal Treatments (DIRT) and Nutrient Network (NutNet)) provide insight into specific processes that are highly relevant in the context of global change.

Increasingly, advanced statistical methods are being used to identify model weaknesses and guide model improvement. In addition to data assimilation techniques, which can be used to calibrate parameters of complex models to diverse data constraints, new tools should be developed to benchmark model performance using observational data sets, and to generate realistic estimates of model uncertainty. Benchmarking tools, such as iLAMB, provide a model-agnostic testbed that moves the field towards automated model diagnostics. The MODEX (model-experiment coupling) approach adopted by DOE emphasizes the use of model predictions to guide experimental design, and experimental results to in turn guide model improvement. The need for rigorous ecological forecasting necessitates such integration of models and both experimental and observational datasets. However, widespread adoption of these approaches will require improved computer and networking facilities that lower barriers to model use and model development. Also required is broader training that integrates cutting-edge tools from computer science and quantitative analytics, including "big data" informatics, statistics, and high-performance computing. Additionally, there needs to be greater emphasis on archiving of data and code in open-access repositories to promote reproducibility and transparency.

Key Priorities:

1. *Identification of:*
    a. *effects of rising atmospheric CO_2 on whole ecosystem carbon balance, and its flux and stock change component, in diverse ecoclimatic settings and in combination with other environmental changes;*
    b. *effects of warming trends and heat extremes on whole ecosystem carbon balance;*
    c. *effects of wetness and dryness trends and variability (including extremes) on whole ecosystem carbon balance;*
    d. *effects of nutrient trends on whole ecosystem carbon balance;*
    e. *interactive effects of these multiple drivers.*
2. *Research focusing on ecoregions with high carbon stocks that are disturbance prone or otherwise vulnerable to release, including peatlands and some forestlands.*

3.3.2 Responses of forest carbon cycling to changes in disturbance regimes and management

Forests constitute the largest carbon sink in North America, but the future of this sink remains unclear given changes in natural and anthropogenic disturbances, trends in forest management and use, and land conversions (Domke et al. 2018). While studies demonstrate the importance of these processes for local to continentals-scale carbon fluxes and stocks (e.g. Amiro et al. 2010, Heath et al. 2011, Goetz et al. 2012, Hurtt et al. 2016, Williams et al. 2016), further study is needed to uncover underlying mechanisms. Process-level studies are needed to characterize the causes of tree mortality, the vulnerability of forests to fires, pests, pathogens, and droughts, as well as the determinants of post-disturbance forest regeneration, composition, and associated effects of forest loss and regeneration on carbon dynamics. Mechanistic understanding of these mortality and recovery dynamics for individuals, stands, and whole ecosystems needs to be incorporated into ecosystem process models to enable skillful projections of how forest carbon stocks and fluxes will respond to anticipated future disturbance regimes. The carbon cycle impacts of changing forest management practices also require focused study, as timber extraction and silvicultural approaches respond to changing markets, including mass timber and engineered wood products, as well as biomass energy. Influences of species selection and the retention or loss of biodiversity associated with harvest and planting, thinning and other treatments modifying forest structure, prescribed burning, fire suppression, the timing of harvest, conservation and assisted migration all remain poorly understood and merit investigation. Full life cycle analysis of carbon is needed to track its fate from forest to product to waste or to the atmosphere as CO_2 or CH_4 (e.g. Figure 3.2.4) Consideration of substitution effects from using forest products in energy and building sectors as a substitute for other fuels and building products is needed as well (see also section 3.3.7).

Continued progress is needed in quantifying and understanding the mechanisms that underlie forest carbon losses and gains, as well as disturbance and recovery dynamics across the continent for an array of forested ecosystems and disturbance types (e.g. Figure 3.2.4), as well as attendant effects on the amount and composition of exports of carbon from forests to downstream ecosystems. Sustained and enhanced remote sensing capabilities will help, including high and moderate spatial resolutions (1 to 100 m) and repeat times (1 to 16 days) from both airborne and satellite sensor platforms (Cohen et al. 2016). Additionally, improved understanding of and CH_4 production, consumption, and release in trees and soils is needed, as well as how they respond to disturbance, forest management, and land-use change.

Addressing these knowledge gaps requires improved integration of methodology and disciplines, enhanced collaboration among scientists and land managers, and sustained support for long-term monitoring and experimental networks. Ecosystem-scale manipulative experiments, and targeted field-based observational studies sampling along gradients of disturbance timing and severity are needed to uncover mortality mechanisms, forest vulnerabilities and thresholds to disturbance, and the determinants of forest recovery patterns. Forest inventory and measurement networks, which have typically focused on aboveground measurements, need expanded sampling of belowground carbon pools and fluxes, in general, and particularly before and after disturbance, management, and land-use change (Smith et al. 2016). Improved integration and synthesis of long-term carbon flux, leaf and canopy physiology, and remote sensing data from networks such as FLUXNET, NEON, and national forest inventory programs should be leveraged to provide complementary, broad-scale mechanistic insights into ecosystem physiology (e.g. Becknell et al. 2015, Williams et al. 2014). Partnerships across disciplines (e.g. foresters, ecologists, statisticians, remote sensing scientists, hydrologists), agencies and institutions (universities, government forest managers, industry, conservation organizations) are providing powerful new synergies and should be actively promoted to spur advances in priority research areas and to develop decision support tools and outreach interactions. Authentic inclusion of actors in business, government and civil society, and potential data end-users, including foresters and land-use planners, in the research planning process is expected to enhance the impact and application of research products, while assisting in the development of standard carbon accounting methods and forest products life cycle analyses (Fahey et al. 2010).

<u>Key Priorities</u>:

1. *Identification of:*
    1. *effects of changing forest management and land use practices on forest sector carbon stocks and fluxes;*
    2. *effects of changing rates, types, and severity of forest disturbances and conversions on long-term ecosystem recovery dynamics and attendant carbon stock and flux dynamics;*
    3. *effects of changing forest composition and structure on forest carbon stocks and fluxes.*
2. *Emphasis on high-carbon, disturbance-prone forest types and regions as well as those with high market value and extractive use.*

3.3.3 Responses of grassland and shrubland carbon cycling to grazing management and invasive species

The grasslands and shrublands of North America are presently believed to constitute a modest net carbon sink in response to fertilization by CO_2 and nutrients (i.e. N deposition), with much of the carbon being stored in soils. Spanning arid to semi-humid environments, these ecosystems are also responding to precipitation variability and trends, as well as background warming that is lengthening growing seasons (Figure 3.3.1). In addition to these climate and CO_2 drivers (addressed in section 3.3.1), grazing practices, invasive species, and woody encroachment, afforestation, and reforestation also have the potential to significantly influence carbon dynamics in grasslands and shrublands of North America in unclear ways over coming decades (Figure 3.3.2).

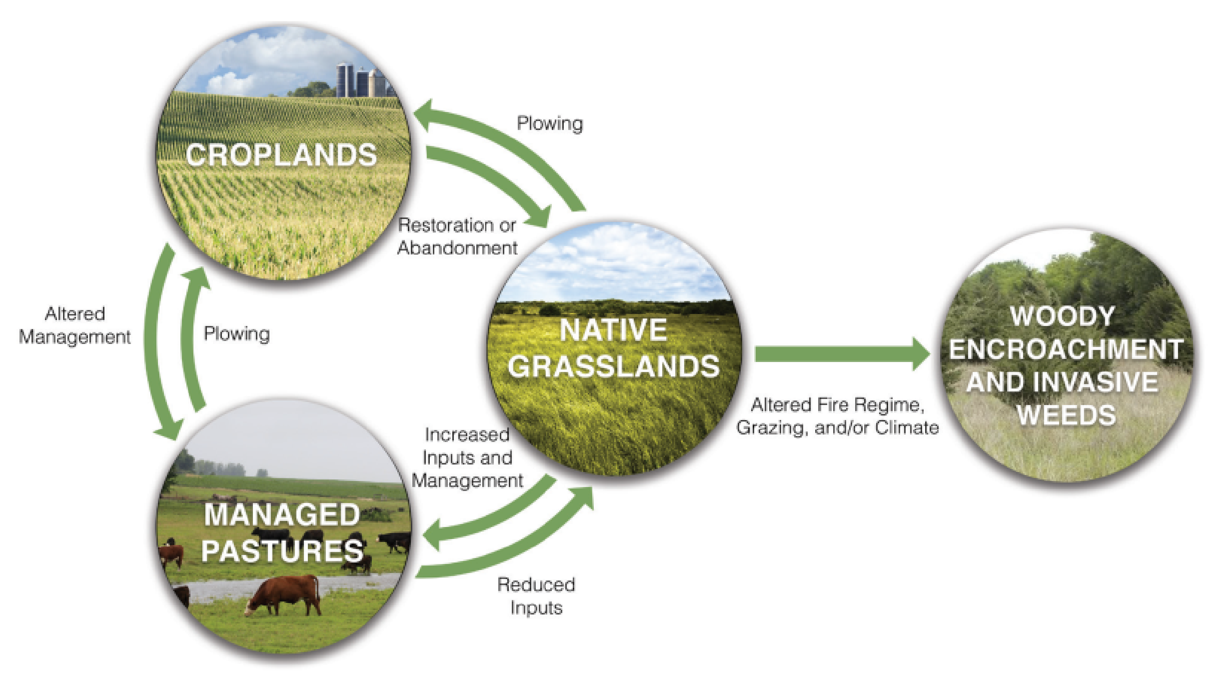

Figure 3.3.2. Management Activities and Their Effects on Grassland Carbon Cycling. Management treatments strongly influence carbon dynamics in grassland, pastureland and cropland settings, and interact with climate trends and variability, rising CO_2 concentrations, invasive species, and fire. [Figure reproduced from SOCCR2, Chapter 10 (Pendall et al., 2018), Figure 10.1, p. 402.]

Grazing acts as a rapid carbon release pathway and may cap carbon accumulation in aboveground tissues and limit the build-up of live, and even dead, carbon stocks. Intensive grassland management with grazing or mowing can stimulate a regrowth response onsite (Owensby et al. 2006) but tends to release carbon to the atmosphere (Klumpp et al. 2009) though not in all cases (Machmuller et al. 2015). Some grasslands are recovering carbon stocks after historical use for agriculture or overgrazing (Conant et al. 2017), whereas others are experiencing invasion by non-native grasses or woody species (Naito and Cairns 2011). For example, reduced fire frequency in mesic grasslands has allowed woody encroachment of juniper which reportedly increased plant and soil carbon stocks (McKinley and Blair 2008), though carbon storage can also decrease with woody encroachment. Widespread invasion of perennial grasslands by annuals (e.g. cheatgrass) can decrease productivity, alter fire frequency, and increase decomposition rates collectively decreasing carbon stocks. Interactions among water availability, grazing intensity, and invasive species strongly influence the carbon balance response to each driver.

Progress is needed to resolve contrasting carbon balance responses to intensive grazing and woody encroachment, in particular, and to advance predictive understanding of their interactions with variability in precipitation. Assessment of continental-scale impacts of changes in these drivers could be achieved with synthesis of existing experimental manipulations, observing networks (e.g. LTER, NEON, AmeriFlux), and targeted sampling along gradients of grazing intensity, woody encroachment, and invasive species. Also needed is upscaling of field-scale process insights to continental-scale process understanding with model-data integration techniques involving spatial statistics, remote sensing, and ecosystem process models.

Key Priorities:

1. *Identification of:*
    a. *determinants of carbon stock and flux responses to changes in grazing practices,*
    b. *the efficacy of innovative grazing management techniques on reducing impacts on soil organic matter depletion and greenhouse gas fluxes, and*
    c. *determinants of carbon stock and flux responses to invasive species and woody encroachment.*
2. *Improved predictive understanding of interactions among grazing, invasive species and precipitation variability in driving carbon stocks and fluxes.*

3.3.4 Responses of local to global carbon dynamics to changes in food production and consumption

Food production and consumption systems have significant impacts on GHG emissions (CO_2, CH_4, and N_2O) (Peters et al. 2016) and constitute one of the largest anthropogenic perturbations to the coupled carbon-climate system. Land conversion and use for cropland and pasture can alter soil carbon stocks, soil nutrition, plant productivity, and erosion rates (e.g. Govaerts et al. 2009, Kopittke et al. 2017, Montgomery 2007, Ogle et al. 2005, Wang et al. 2017). Food production systems introduce greenhouse gas emissions from enteric fermentation, fertilization, waste streams (e.g. manure), and mechanization (e.g. farm equipment) (e.g. Montes et al. 2013). Land use and dietary choices significantly alter how food systems influence the coupled carbon-climate system (e.g. Paustian et al. 2016, Clark and Tilman 2017, Rosi et al. 2017, Steinfeld and Gerber 2010) (Figure 3.3.3). Food systems are, in turn, altered by changes in the environment (e.g. climate, atmospheric composition, and soils), as well as by technological and societal conditions (e.g. farming practices, markets and lifestyles).

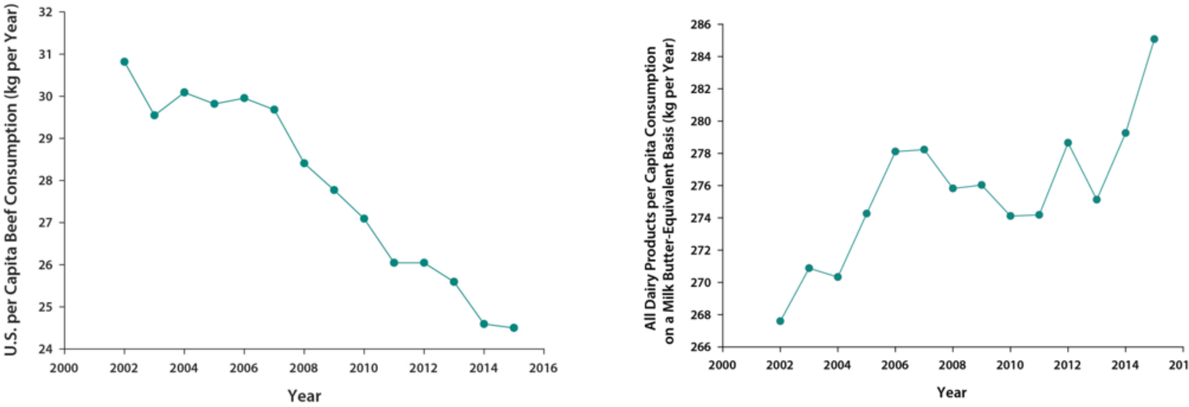

Figure 3.3.3. Food Sector Trends Can Strongly Influence the Carbon Metabolism of Society. Trends in the food sector, such as declining carbon-intensive beef consumption but increasing dairy consumption, can significantly influence emissions from the broader agriculture, forestry, and land use (AFOLU) sector. [Figure reproduced from SOCCR2 Chapter 5 (Hristov et al. 2018), Fig 5.3 and 5.4, p. 241 and 242].

Improved mechanistic understanding is needed to clarify how and why plant productivity, soil carbon stocks, and lateral carbon flows (e.g. erosion, harvesting) change with a range of agricultural management practices. This requires process studies quantifying carbon flows and stocks, as well as hydrologic, biologic, and physicochemical conditions over time with land conversions and in response to alternative management regimes. This can be achieved with a complement of targeted monitoring of existing sites in use and naturally undergoing alternative treatments, as well as experimental manipulations, and chronosequence studies. Key science questions center on how soil organic carbon and plant productivity respond to changes in biomass carbon inputs, erosion and soil structure, changes in tilling, conventional versus organic practices, soil fertility and fertilization, and crop rotations, multi-cropping and fallowing.

Global demand for meat has created widespread and growing production of livestock for human consumption. Process studies to improve understanding of greenhouse gas emissions associated with alternative management practices within livestock operations are needed. In particular, studies are needed on the emissions from alternative feedstocks (grass or grain fed), meat sources (e.g. ruminant versus monogastric), manure management strategies (manure solids separation, aeration, acidification, biofiltration, composting, and anaerobic digestion), and farming systems (conventional or circular economies). Investigations are needed of the GHG implications of human food waste and food choices. Emphasis should be placed on quantitative studies assessing the effects of different diets, clarifying the relative efficiencies of different food sources in terms of land area, water resource use, caloric and energetic losses through the production system, food waste with consumption, and including life cycle assessments (LCAs) of the full GHG emissions embodied in the production and consumption of different food sources. Studies are also needed to document carbon cycle implications of future afforestation, reforestation, and deforestation in response to shifting global patterns of agricultural production.

Key Priorities:

1. *Full life cycle assessment of carbon stock and flux responses to alternative cropland management practices, with associated greenhouse gas budgets, and to alternative food production systems, each with associated greenhouse gas budgets.*
2. *Emphasis on comparisons among food system alternatives including their capacities to meet caloric, nutritional, and dietary preferences and requirements, and potential for greenhouse gas emissions reductions.*

3.3.5 Responses of aquatic carbon dynamics to changing carbon inputs, nutrient loadings, warming, and direct physical alterations

Aquatic systems, including wetlands, streams, rivers and estuaries, play a major role in the continental carbon cycle. For example, organic soil wetlands (peatlands) only occupy 3% of global lands but store 30% of the soil carbon. Aquatic systems store, emit, and laterally transport carbon along a continuum from upland to coastal waters. As recipients of upland carbon via erosion and dissolved loads, aquatic systems are also driven by all of the forcings affecting terrestrial ecosystems including rising atmospheric CO_2 concentrations, nutrient fertilization, climate change, and land cover and land use changes. Warming and nutrient loadings are directly altering their metabolism and biogeochemical transformations. Aquatic systems are also being physically transformed by wetland destruction and creation, waterway alterations (e.g. channelization), impoundments, and tile drainage. Detailed quantitative and mechanistic understanding of these processes is incomplete.

Progress is needed in understanding the relative contributions of diverse carbon inputs (e.g. allochthonous, autochthonous, and geochemical contributions) as they vary across diverse physiographic and ecoclimatic settings and in time. Advances are needed to understand the processes controlling the magnitude and timing of CH_4 and CO_2 fluxes from aquatic systems, as well as productivity and respiration rates within wetland, riverine, lacustrine, and estuarine settings. The determinants of rates of sedimentation and release in inland waters (e.g. reservoirs) need to be resolved, along with impacts of channelization, levees, coastline developments, and wetland alterations on erosion, sedimentation, and conveyance. Effects of dam removal and flooding on carbon storage and release needs further study. New insights on how all of these processes are responding to changing hydrology, nutrient inputs, agricultural runoff, and eutrophication are needed. Advances are needed to translate site-level and case study process understanding to integrated, system-level behavior at watershed to continental scales, with improved scaling methods, and system-wide modeling that considers soil attributes (organic and mineral contents), spatio-temporal patterns of inundation, nutrient dynamics, connections to upland systems (i.e. terrestrial-aquatic interfaces), decomposition and transformation processes. Lastly, a modeling framework is needed to represent the aquatic carbon cycle fully integrated with terrestrial and oceanic carbon exchanges and capable of prediction.

Key Priorities:

1. *Identification of:*
    a. *lateral fluxes, emissions, and full budget assessments considering diverse inputs, changes in stocks, and outputs for all C forms (DIC, DOC, POC, CO_2, and CH_4);*
    b. *how water column chemistry and biology influences the fate of C and permanence of C sinks;*
    c. *effects of terrestrial wetland destruction, creation, and restoration on C emissions and transport*;
    d. *carbon burial rates (including use of isotopes in sediments) and fate of this buried carbon (respired vs. preserved).*
2. *Improved scaling methods, and system-wide modeling capabilities to translate site-level and case study process understanding to integrated, predictive, system-level behavior at watershed to continental scales.*
3. *Incorporation of carbon dynamics of freshwater and estuarine ecosystems into coupled land-ocean process models taking account of interactions with terrestrial and oceanic carbon cycle processes.*

3.3.6 Responses of coastal and oceanic carbon dynamics to temperature, water quality, acidification, and marine carbon dioxide removal approaches

The coastal environment, spanning from wetlands and estuaries across the shallow ocean shelf and onto the continental slope, is a region of vigorous biological productivity and biogeochemical transformations, lateral carbon transport, and carbon storage (Najjar et al., 2018). Human disturbance is altering both the carbon and biogeochemical inputs to the coastal system (Regnier et al., 2013). Disturbances include nutrient pollution, destruction of wetlands, rising atmospheric CO_2, ocean warming, acidification, hypoxia, and other aspects of climate change affecting freshwater input, upwelling, currents, winds, and sea-level rise.

An improved mechanistic understanding of the coastal carbon system requires embedding targeted process and attribution studies within a framework of an expanded marine biogeochemical monitoring system that characterizes temporal and spatial variability of the carbon budget as well as long-term trends. Key scientific questions for process and attribution studies include (a) the factors driving changes over time of coastal surface ocean CO_2 and air-sea exchange including ocean carbon uptake, climate change, and alterations in wetland carbon fluxes (Reimer et al., 2017); and (b) the response of water-column biogeochemistry, carbon export and fluxes, and ecosystem dynamics to multiple stressors; and (c) the burial, mobilization, and fate of organic carbon storage in coastal sediments, marshes, mangroves, estuaries, and seagrass meadows (McLeod et al., 2011). More comprehensive synthesis and attribution studies that leverage available coastal and ocean observations are needed, similar to prior and current investments in long-term observations of terrestrial systems (e.g., AmeriFlux).

Ocean acidification, caused by rising atmospheric CO_2 and ocean uptake, is a growing concern for coastal systems because of the wide range of possible negative impacts on marine life (Kroeker et al., 2013). Excess CO_2 reacts with water resulting in a series of chemical changes including lowering pH, carbonate ion (CO_3^{2-}) concentrations, and the saturation states for carbonate minerals used by many organisms to construct shells and skeletons. Acidification in coastal waters can be exacerbated by nutrient eutrophication, atmospheric deposition of acidic compounds, and other local pollution sources (Strong et al., 2014).

Improved evaluation of the biological impacts of ocean acidification requires a combination of sustained ocean CO_2 and biological system observations, targeted manipulation experiments on key biological species, and field and ecosystem-level process studies. Calcification by warm-water and cold-water corals and coralline algae appears particularly sensitive to reductions in carbonate ion concentration and mineral saturation states, as shown by numerous laboratory and mesocosm studies. Recent novel field manipulation experiments of water chemistry on shallow coral reefs open up critical opportunities for assessing community-level responses (e.g., Albright et al., 2018). Acidification vulnerabilities for many shellfish – clams, scallops, oysters, crabs – with possible repercussions for many valuable US and international commercial fisheries (Gledhill et al., 2015; Hare et al., 2016); further studies are needed on shellfish as well as expanding further into assessing impacts for key crustaceans and finfish (cf. Bednaršek et al 2021; Williams et al. 2019). During the mid-2000s, low pH waters associated with coastal upwelling led to reduced larval survival of Pacific oysters in some US Pacific northwest shellfish hatcheries, a problem that has been largely addressable so far through adaptive strategies (Barton et al., 2015). The challenges and potential adaptation strategies for wild-caught species are generally less well-known and require more detailed study. For all marine species, the impact of current and future ocean acidification must be framed in the context of a rapidly changing ocean environment with multiple human-driven stressors, particularly ocean warming (Breitburg et al., 2015).

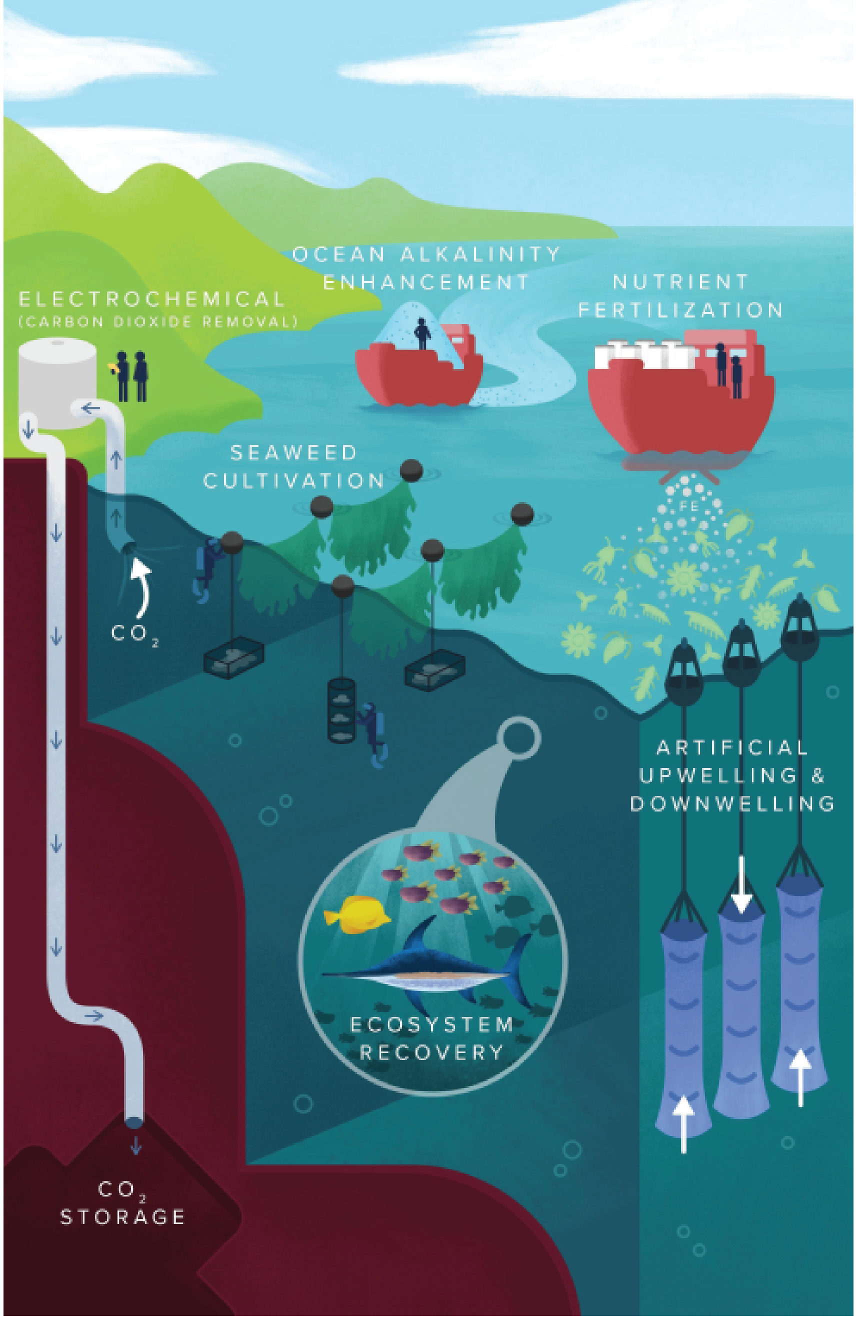

Figure 3.3.4. Ocean-based Carbon Dioxide Removal approaches under consideration. [Figure reproduced from NASEM report (National Academies of Sciences, Engineering, and Medicine 2021), Fig S1, p. 4].

Finally, as industrial and legislative actors in the US are proposing numerous studies on marine carbon dioxide removal (mCDR), the NACP community should engage in process studies to ascertain the efficacy and ecosystem impacts of the proposed mCDR approaches: seaweed cultivation, nutrient fertilization, artificial upwelling and downwelling, ocean alkalinity enhancement, ecosystem recovery, and electrochemical carbon dioxide removal (National Academies of Sciences, Engineering, and Medicine 2021) (Figure 3.3.4).

Key Priorities:

1. *Identification of:*
    a. *the major factors driving changes over time of coastal surface ocean CO_2 and air-sea exchange including ocean carbon uptake, climate change, and alterations in wetland carbon fluxes;*
    b. *the response of water-column biogeochemistry, carbon export and fluxes, and ecosystem dynamics to multiple stressors; and*
    c. *the burial, mobilization, and fate of organic carbon storage in coastal sediments and especially in so-called blue carbon in marshes, mangroves, estuaries, and seagrass meadows*
    d. *the biological impacts of ocean acidification.*

3.3.7 Responses to changes in energy, transportation, and building/housing sectors

North America's electric power production and distribution systems, as well as its highway, railway, and airway transportation systems are some of the world's largest, generating a correspondingly large proportion of global carbon emissions (Marcotullio et al, 2018) (Figure 3.3.5). Fossil fuels dominate the region's total energy supply (US EIA, n.d. a,b), with North America's energy consumption contributing significantly to global carbon dioxide equivalent (CO_2e) emissions. The region emits approximately 17% of total global GHGs from fossil fuels and cement production (Boden et al., 2017). Emissions from transportation, electricity generation, and industry each account for about one third of the total, with more modest contributions from commercial and residential uses.

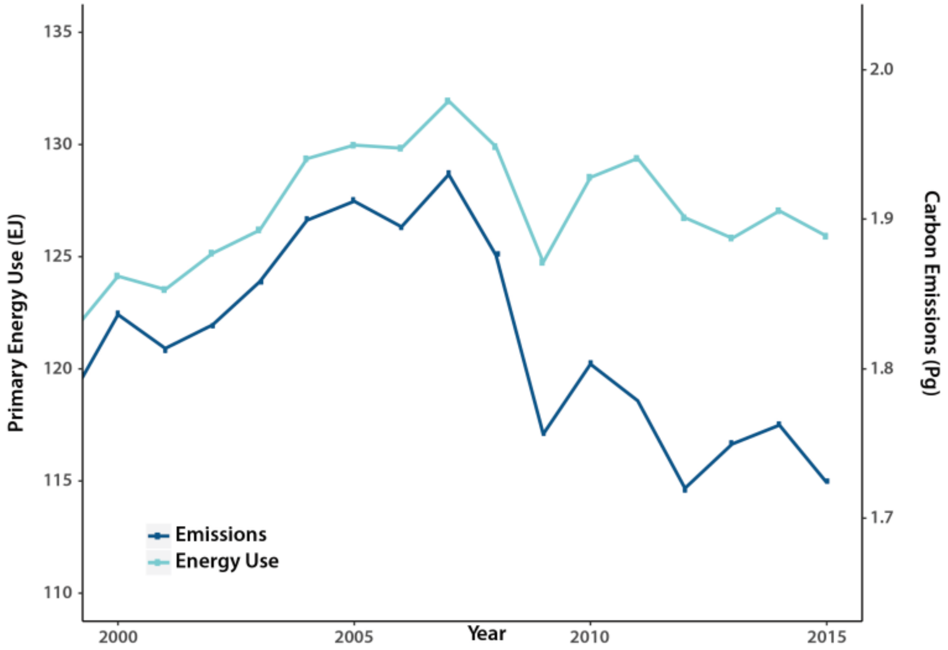

Figure 3.3.5. North American Primary Energy Consumption and Carbon Emissions, 2000 to 2015. Energy use in exajoules (EJ); carbon emissions in petagrams of carbon (Pg C). [Figure reproduced from SOCCR2, Chapter 3 (Marcotullio et al. 2018), Figure 3.4, p. 128]

The region also contributes significantly to worldwide energy production and energy reserves from fossil fuels spanning coal, natural gas and oil and petroleum hydrocarbons (BP 2018; DOE EIA, 2016). Trends in anthropogenic emissions of CO_2e are being driven by changes in the fuel mix, such as increases in natural gas and renewables (Figure 3.3.6 and Figure 3.3.7), and by a variety of new, less carbon-intensive technologies. Those drivers are, in turn, being influenced by changes in the price of fuels, by slow growth rates in electricity demand in the United States and Canada, and by national, state and regional policies that are promoting technology development for energy efficiency and clean energy (Marcotullio, et al 2018).

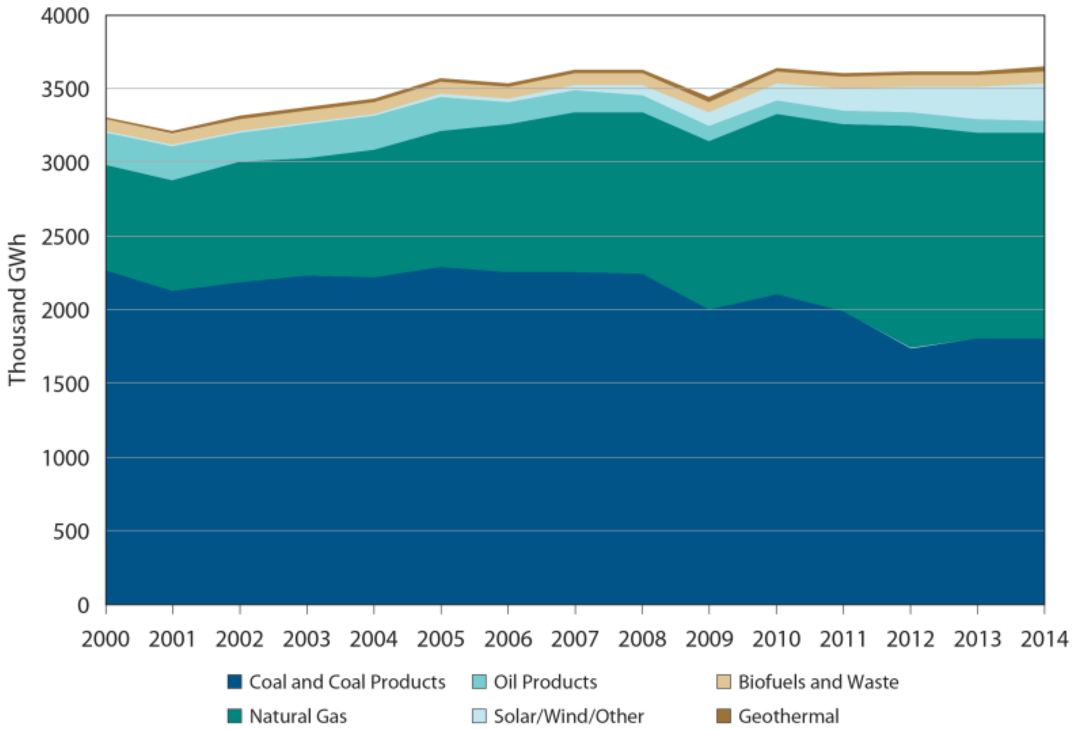

Figure 3.3.6. Renewable and Fossil Fuel Electricity Production in North America, 2000 to 2014. Electricity production by energy source is reported in gigawatt hours (GWh). [Figure reproduced from SOCCR2, Chapter 3 (Marcotullio et al. 2018), Figure 3.7, p. 132]

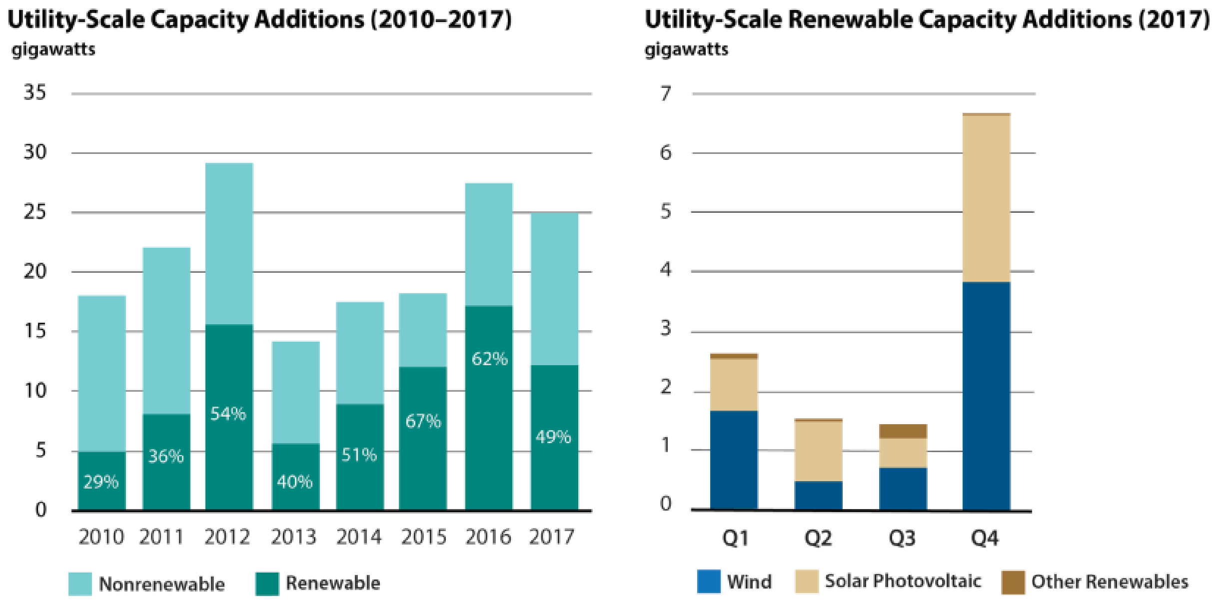

Figure 3.3.7. Annual Utility-Scale Energy Generation Capacity Additions in North America, 2010 to 2017 and the Distribution Across Types of Renewable Energy in each Quarter of 2017. Energy

generation capacity reported in gigawatts. [Figure reproduced from SOCCR2, Chapter 3 (Marcotullio et al. 2018), Figure 3.8, p. 133]

Five areas in the energy system stand out as needing further examination and research. First, the governance and institutional needs in the transition to a low-carbon society are not well understood. 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. 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 is not well understood. Second, investigations are needed to comprehensively assess the capacity of renewable energy to supply current and future demands, with attention to intermittency in production, energy storage, energy transmission, and the typically low energy densities of solar and wind sources which require large surface areas to meet demands. Third, energy use efficiencies in households and public and private sectors are recognized to be an important component of reducing energy use but with unclear scope. Also, such gains are at risk of being masked by overwhelming growth in additional demand. Fourth, 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." However, the actual amount of gas that escapes as leakage and fugitive emissions has yet to be measured accurately. Lastly, detailed comparable data for end-use energy, emissions, and projections across North American economies have yet to be generated, and more comparable economic end-use data across nations could help inform evidenced-based regional policies regarding carbon management (Marcotullio et al 2018).

Key Priorities:

1. Identification of:

  a. *impacts of changes in fuel sources and energy sources, considering energy density and distribution issues, market constraints and opportunities*
  b. *governance and institutional needs in the transition to a low-carbon society*
  c. *scope for renewables to contribute a growing fraction of total energy consumption*
  d. *scope for energy use efficiencies in households and public and private sectors in the face of growing energy demands*
  e. *leakage and fugitive emissions of CH_4 during production, distribution, and use*
  f. *improved data collection on energy uses and emissions across North American economies*

3.3.8 Responses to changes in industrial, commercial, public, and household production and consumption

Industry, commerce, manufacturing, governance, residential life and the general functioning of society all influence the patterns and trends of carbon fluxes and stocks in natural and managed ecosystems, and in the built environment. The decisions and actions these entities take can have profound effects on the carbon metabolism of society and on its attendant impacts upstream in fields, farms, forests, waterways and beyond, and they are driven by a wide range of factors including policy, economic, and technology drivers (Figure 3.3.8).

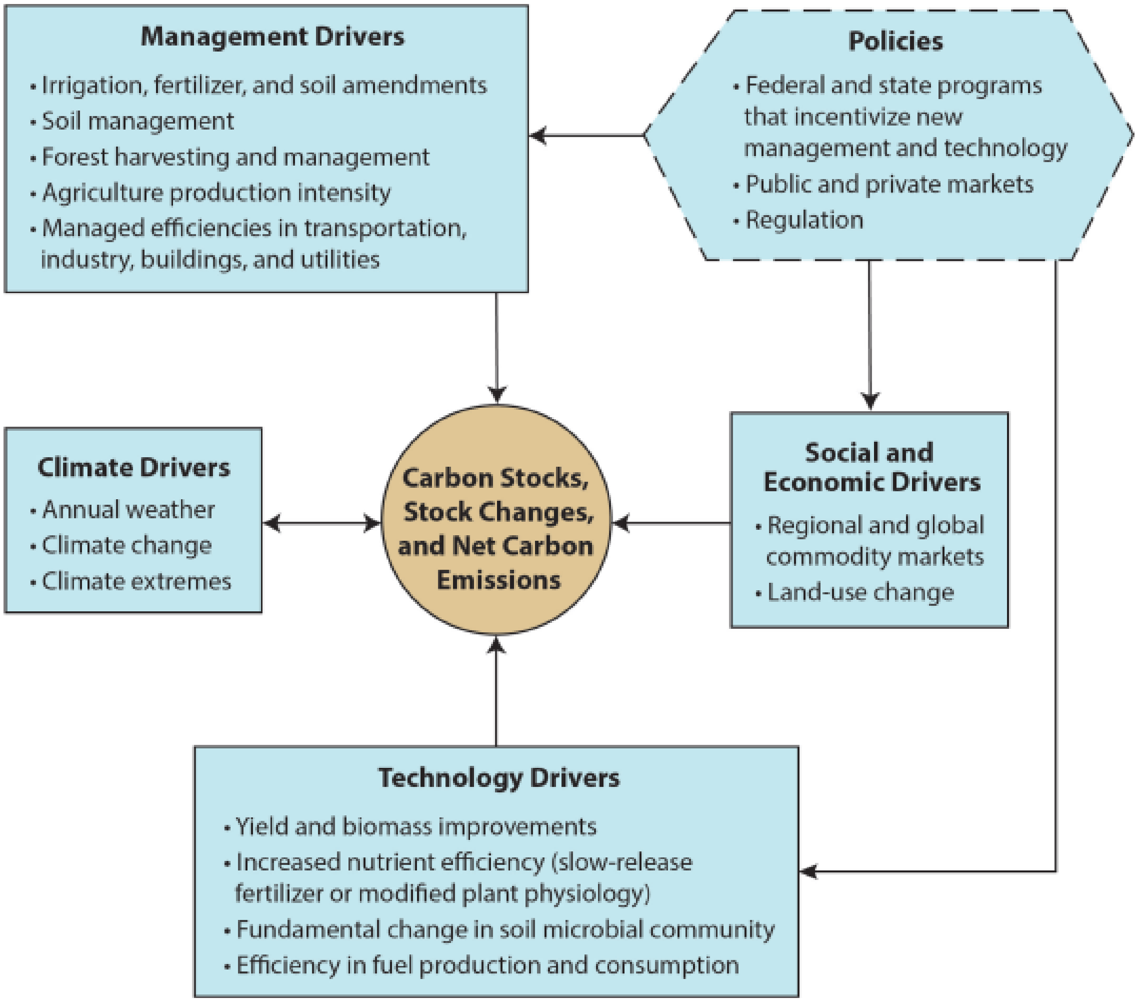

Figure 3.3.8. Primary Drivers of Carbon Stocks and Emissions in Select Societal Sectors. Carbon and carbon dioxide (CO_2) estimates can be generated using observations, models of differing complexity, or both. To understand and estimate future carbon stocks and emissions, drivers of carbon stock changes and carbon emissions must be considered and represented. This schematic illustrates examples of components needed to represent carbon stock changes prior to addressing policy drivers. [Figure reproduced from SOCCR2, Chapter 18 (West et al., 2018), Figure 18.1, p. 730.]

Studies are needed to uncover how the production and sales of goods and services influences the carbon cycle through resource extraction, building, transportation, energy use, material consumption and associated wastes. Investigations into the potential effects of changes in policies, market forces, and decision making are needed, with an eye toward developing predictive capabilities to facilitate assessments of likely outcomes of actions being considered by decision makers. Methodological advances in tracking, tracing, reporting and visualizing the direct material flows of carbon resulting from these production and consumption activities are needed, along with communication of the carbon embedded in these activities.

Key Priorities:

1. *Identification of:*
    a. *carbon cycle impacts of expansion of built environments and shifts in building materials*
    b. *carbon cycle implications of waste trends such as in sewage and landfills*
2. *Research on the potential effects of changes in policies, market forces, and decision making, with an eye toward developing predictive capabilities to facilitate assessments of likely outcomes of actions being considered by decision makers*
3. *Improved methods for tracking, tracing, reporting and visualizing the direct material flows of carbon resulting from these production and consumption activities*

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Chapter 3.4. Predictions: Model Development, Evaluation and Prediction

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3.4.1 Introduction

The 2011 US Carbon Cycle Science Plan listed ‘prediction’ as one of several overarching science goals, specifically asking how to improve predictions of ‘how ecosystems, biodiversity, and natural resources will change under different CO_2 and climate change scenarios?’ This Chapter describes for the Science Implementation Plan five thematic areas that need to be developed to improve our predictive capabilities for a biosphere under increasing anthropogenic pressure. These include (i) expanding the role of forecasting and treatment of uncertainties, (ii) the use of benchmarks for model evaluation and initialization, (iii) applications of Observing System Simulation Experiments (OSSEs), (iv) consideration of feedbacks, and (v) new focus areas, including addressing social systems and the role of lateral fluxes along the land-ocean atmosphere continuum (LOAC).

Predictions are useful for many applications, including informing management decisions and policy targets, evaluating how well we understand a particular system and its potential feedbacks, and prioritizing and optimizing *in situ* or remote sensing-based monitoring strategies. Predictions can take place at varying timescales, with *forecasts* (seasonal-to-subseasonal, i.e., S2S) that aim to provide information for daily to sometimes decadal time windows and *projections* typically for multi-decadal to millennial timeframes, depending on the purpose of the scenario. In addition to constraining what might take place in the future, ‘predictions’ can be made for historical periods; ‘retrospective forecasts’ or ‘hindcasts’ are commonly used to evaluate model skill and ‘reanalyses’ are generated by fusing hindcasts with observations to reconcile historical pools and fluxes. This chapter focuses mainly on the use of predictions made for seasonal to century scale processes and their relevance for process understanding and informing policy.

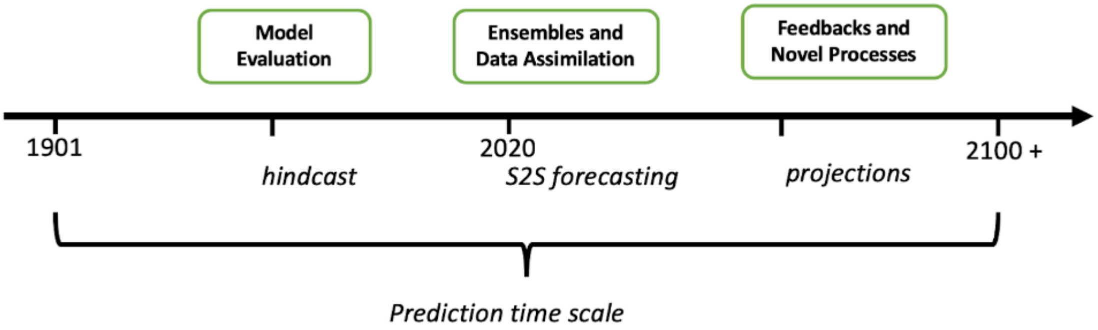

Figure 3.4.1: Prediction Time Scales for Different Kinds of Modeling Activities. This chapter provides a perspective on 'predictions' considering the role of hindcasts, forecasts and long-term projections has in model ecosystem response to global change.

Rapid and large-scale changes are taking place within Earth's climate system, in atmospheric trace gas concentrations (e.g., CO_2, CH_4, N_2O, O_3, $PM_{2.5}$), on the land surface through deforestation, forest management, and cropland expansion and in the hydrologic cycle through water use and changes in water quality. The rate and magnitude of these changes, interactions between drivers, and feedbacks from the biosphere and atmosphere have led to conditions that lack any historical or paleoecological analogs that can appropriately inform the future. For example, the last time atmospheric carbon dioxide levels were more than 415 ppm (as of 2020) was more than several million years ago, and thus it is not straightforward to make empirical inferences to learn how ecosystems will respond as CO_2 concentrations continue to rise into the 21st century. Consequently, modeling tools used in prediction must incorporate interactions and nonlinear feedbacks between a range of processes that operate at varying temporal and spatial scales, e.g., interactions between CO_2 and air pollutants on ecosystems. These models tend to be mechanistic or process based, in that they use first principles to represent flows of carbon, water, energy and nutrients with various parameters and requirements for 'driver' data (i.e., climate, CO_2, and land-use scenarios). More recently, data-driven models based on machine learning, deep learning and artificial intelligence frameworks are demonstrating important and useful predictive capabilities (Reichstein et al., 2019). This Chapter focuses on the requirements and areas of emphasis for improving process-based modeling approaches to be used in making predictions.

3.4.1 Forecasting and Uncertainty

There are large uncertainties in (and among) simulated projections of historical and future changes in carbon cycling (e.g., Ciais et al. 2013; Anav et al. 2013; Arora et al. 2013; Friedlingstein et al. 2014) (Figure 3.4.2), which inhibit our ability to understand and forecast changes in climate feedbacks and ecological services. Foundational to the goal of reducing these are (1) the establishment of probabilistic forecasting as a community standard for how predictions and projections are made, and (2) a systematic effort to understand better which uncertainties, i.e., parameters, processes, and drivers, limit forecasts at different spatial and temporal scales. Probabilistic forecasting is widely considered best for representing the uncertainties in meteorological forecasts, but traditionally has not been the norm in carbon cycle modeling. Ensemble approaches are becoming more common, but to date have focused on subsets of uncertainties. The lack of a full error accounting means we do not yet know the relative importance of different uncertainties, which constrains our ability to prioritize which uncertainties to focus on reducing.

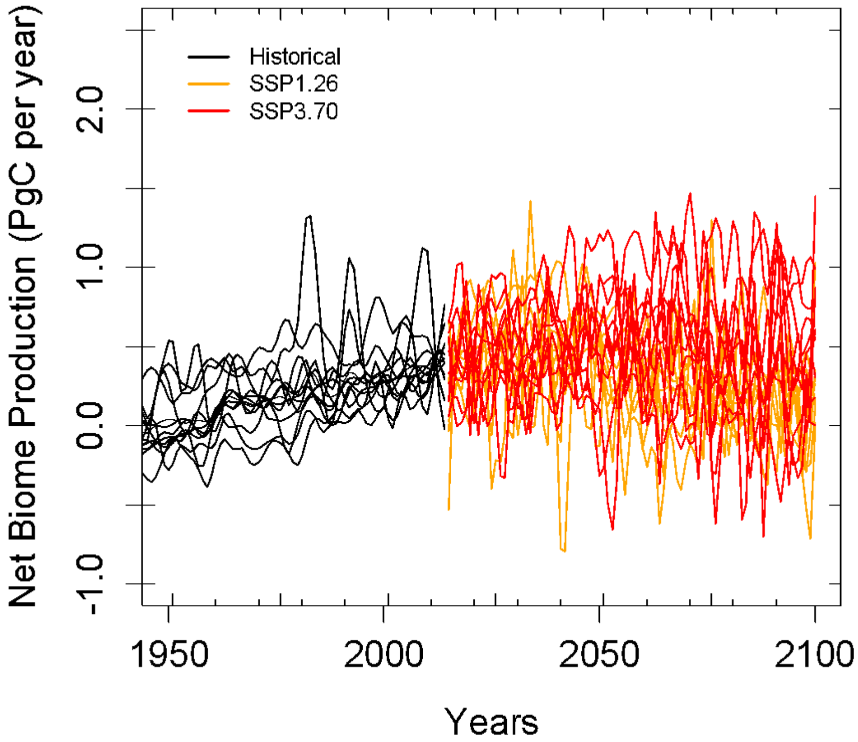

Figure 3.4.2. Annual Net Biome Production from Terrestrial Biosphere Models for North America. Ecosystem carbon balance responses to contemporary drivers such as elevated CO_2 and climate change remain uncertain, with model projections showing widespread and large variability. [Credit: For data preparation of CMIP6 archive, Chris Jones (Met Office)]

Broadly speaking, our ability to make a skillful carbon cycle forecast is limited by five key uncertainties: i) initial conditions, ii) external drivers and boundary conditions, iii) parameter uncertainty, iv) parameter heterogeneity, and v) process error (Dietze 2017). The initial condition of model state variables drives significant uncertainty in short-term predictions and can also be significant at much longer timescales, e.g. changes in soil carbon pools, disturbance, vegetation succession, and species range shifts that can play out over centuries to millennia (Huntzinger et al. 2020). For example, research suggests that model initialization limits the detectability of changes in terrestrial carbon cycle pools for multiple decades (Lombardozzi et al. 2014). Boundary conditions and model drivers are another source of uncertainty, as there is considerable uncertainty about future climate, deposition, disturbance, etc. This will translate into variability in terrestrial carbon cycle pools (Matthews et al. 2004) and other ecosystem services, such as projected crop yields

(Levis et al. 2016). An additional source of uncertainty arises from model process error, including the failure to represent either stabilizing or destabilizing feedbacks, the inherent stochasticity in biological processes (dispersal, mortality, disturbance), and the omission or misspecification of processes that become important as models are applied at spatial or temporal scales different from the scale at which they were parameterized. Many studies, for example, have highlighted the large carbon cycle uncertainties that arise from the various representations of photosynthetic processes (Dietze et al. 2013; Fatichi et al. 2014; Rogers et al. 2017; Lombardozzi et al. 2015, 2018), yet photosynthesis has received more attention than arguably any other process in carbon cycle models. Process errors encompass the 'residual' differences between models and observations, after observation errors have been accounted for, but are rarely accounted for in carbon cycle forecasts (Raiho et al., 2020). Parameter uncertainty arises because most of the parameters in carbon cycle models are not physical constants but empirical coefficients that need to be estimated from observational data. Finally, parameter heterogeneity occurs because many ecological processes can be highly variable in space and time for reasons that are incompletely understood (e.g. trait plasticity), but which can nonetheless be accommodated using approaches such as statistical random effect or spatial maps of trait variability. The combination of these uncertainties limits the predictability of carbon cycling, but targeted research to quantify the uncertainties will help prioritize research efforts and improve carbon cycle forecasting.

Recent analyses by Lovenduski and Bonan (2017) and Bonan and Doney (2018) quantified these sources of uncertainty and illustrated that "model error" accounts for nearly 80% of uncertainty in carbon cycle projections over the next century. These initial efforts, however, combined multiple sources of uncertainty within a single "model error". Efforts to disentangle these uncertainties point to large contributions from process and initial condition error, but have been limited to simple models and local scales (Raiho et al. 2020). Progress on quantifying and reducing uncertainties can be made through several paths, including: explicitly quantifying parameter uncertainty by combining trait constraints and Bayesian calibration; data assimilation to constrain initial conditions based on observations rather than spin-up; employing statistical model selection and hierarchical approaches; using optimality theory models; model benchmarking and inter-comparison (see 3.4.2) and acknowledging, quantifying, and propagating the process error in current semi-mechanistic process-based models. Research is required to determine the most scientifically rigorous and effective methods for treating initial conditions and model spin up for ecosystem carbon cycle models, with consideration that ecosystems are never in steady state.

Other, more systematic ways that the scientific community can reduce uncertainty in carbon cycle projections and improve carbon cycle predictability and forecasts require more sweeping initiatives. One such initiative would be to implement a comprehensive carbon-cycle reanalysis through a formal model-data assimilation of ground, tower, and remotely sensed observations, similar to meteorological reanalysis products. Efforts to develop such assimilation systems for the carbon-cycle are in their early stages (e.g., NASA Carbon Monitoring System), and as they mature they will ultimately link top-down inversions (e.g., CarbonTracker) with bottom-up syntheses and facilitate analysis of spatial and temporal variability in carbon pools and fluxes, and help us identify model structural errors. Additionally, carbon-cycle reanalysis would provide an improved operational tool for land carbon monitoring, reporting, and verification requirements under the Paris Climate Accord, the UN Framework Convention on Climate Change, and REDD+, while enabling a seamless transition to forecasts with constrained initial conditions.

A second proposed initiative is to implement a carbon cycle forecast program that creates near-term (sub-daily to multiple years) iterative forecasts as a way to accelerate understanding and make carbon cycle predictions more relevant to real-time decision making (Dietze et al. 2018). Existing ecological monitoring networks such as FLUXNET, NEON, national forest inventories, etc., can be leveraged for this purpose, strengthened with new data sources e.g., tree rings, lidar, imaging spectroscopy, and assimilated together to produce rolling forecasts – predictions produced and tested against new data on a continuous basis. Other processes that we can forecast rapidly, including vegetation phenology, ecosystem fluxes, and disturbances like insect outbreaks, can be used for carbon cycle and adaptive management, providing immediate feedback to land managers. For example, the IPCC 1.5 Degree Special Report underlines the need for rapid action (IPCC, 2018), a 2019 report by the US National Academies of Sciences, Engineering, and Medicine offers four "negative emissions technologies" as a proposed set of such actions (National Academies of Sciences, Engineering, and Medicine, 2019), and a 2022 report by the US National Academies of Sciences, Engineering, and Medicine explores possible ocean-based carbon dioxide removal and sequestration opportunities (National Academies of Sciences, Engineering, and Medicine, 2022); here we emphasize the need for rapid learning to accompany that, via a more systematic focus on uncertainty and more intimate feedbacks between monitoring, forecasting, and management.

3.4.2 Establishing Benchmarks

Improved model representation of ecosystem processes and biogeochemistry–climate feedbacks are essential for reducing uncertainties in climate change predictions. The increasing complexity of carbon cycle models, however, requires a comprehensive and detailed evaluation of model fidelity to identify model weaknesses, inform design of new measurements and field campaigns, achieve better understanding of controlling processes, and yield improved predictions. Community efforts to coordinate model assessment methodologies and quantitative metrics of model performance through standardized open source software tools enables systematic benchmarking across models and modeling centers e.g., iLAMB, ESMValTool. Ideally, benchmarking systems help researchers avoid "reinventing the wheel" by performing data preparation, regridding, and standardized gap-filling, as has been done for many ocean carbon data sets (e.g., Sabine et al. 2013; Bakker et al. 2016; Lauvset et al. 2018; Olsen et al. 2020; Jiang et al. 2021). Using community accepted datasets also ensures that all users are comparing against the same data.

Recent coordinated, international efforts have focused on defining community-wide reference data sets, methods, and metrics for model evaluation (Abramowitz et al. 2012; Kumar et al. 2012; Collier et al. 2018). These are built on data ranging from point to global scales, and from centennial to diurnal time scales. The FLUXNET network of eddy covariance towers, which measures the exchanges of heat, water, and trace gases, has been incorporated into several model benchmarking systems for both carbon dioxide and methane (Abramowitz et al. 2012; Blyth et al. 2011; Lawrence et al. 2019). Single eddy covariance or long-term ecological 'super' sites are useful for evaluating process-level responses of selected ecosystems.

Global-scale collaborative efforts for model benchmarking include iLAMB (Collier et al. 2018), ESMValTool (Eyring et al. 2016) and the land surface verification toolkit (LSVT; Kumar et al. 2012). Each product compares current models against observations related to biogeochemistry, hydrology, radiation and energy, and climate forcing. iLAMB and ESMValTool also facilitate evaluation of future CMIP models. For example, ESMValTool includes tools to reproduce well-established evaluations of CMIP5 models, such as emergent constraints to investigate model biases in interannual variability of carbon uptake (Cox et al. 2013) or gross primary productivity (GPP) response to CO_2 (Wenzel et al. 2016).

Benchmarking systems often produce a final metric defining the performance of the model(s), but this should be seen as the beginning of model development and process understanding, not the end. To enable future development that improves model prediction, a process is needed to identify which metrics are most valuable for determining prognostic skill (which will likely depend on the applications of the model), and to identify the relevant observations or experiments to assess these metrics. Often, benchmarking can flag missing datasets as well as highlight model predictive deficiencies. The wealth of North American carbon cycle data, including the Free Air CO_2 Enrichment (FACE) experiments, ecosystem experiments (e.g., summarized by INTERFACE), nutrient addition, and warming experiments, should be used to test and develop predictive models. The inclusion of global change experiments in benchmarking datasets will facilitate future model development, and will help identify instances when future model development improves model performance in one component but degrades model performance in a separate but related component. Benchmarking metrics should account for process-level and emergent behavior of the coupled system, including the equilibrium climate sensitivity and the transient climate response, rather than just the mean state (e.g., annual average GPP).

A challenge with benchmarking is understanding the limitations of the observations: multiple data sets can sometimes give conflicting results, and benchmarks need to account for measurement error and uncertainty (for example relating to natural climate variability). When datasets used in benchmarking packages do not include carefully quantified uncertainty bounds, it is difficult to determine whether or not the model actually has a bias (this is a problem for all model evaluations and is not unique to benchmarking). And when not possible, this highlights a need for uncertainty quantification from the measurements.

3.4.3 Observing System Simulation Experiments (OSSEs)

Observing System Simulation Experiments, or OSSES, provide a unique approach to help inform prediction by incorporating observations within a sampling efficiency framework. First developed to understand meteorological modeling and forecasts, OSSEs are modeling studies that sample simulated processes through a workflow that is representative of observational networks and conditions, and then use these simulated samples to inform Reanalysis models. The comparison between prior conditions and the Reanalysis outputs indicates how well the sampling network can inform our process understanding. In the context of the carbon cycle, the OSSE workflow has been adapted to inform terrestrial and ocean observing networks, mainly through the evaluation of greenhouse gas satellites.

For example, recent spaceborne carbon observatories, such as the NASA Orbiting Carbon Observatory 2 (OCO-2) and the Orbiting Carbon Observatory 3 (OCO-3, aboard the International Space Station), are being used to observe column concentrations of atmospheric CO_2. To better understand how well these observations can inform us on terrestrial and oceanic carbon fluxes, OSSEs have been developed to quantify effects of cloud-cover, aerosols, and water-vapor concentrations on CO_2 retrievals and ultimately the derived surface fluxes and emissions of carbon. The workflow is similar to how the meteorological community has used OSSEs: a land-surface model provides fluxes, these fluxes are ingested within an atmospheric model to generate column concentrations, the column concentrations are sampled following greenhouse-gas satellite configurations, and the samples are used within an atmospheric inversion model, and the posterior fluxes compared with the original surface flux.

The relevance of OSSEs for predictive modeling is unique in that these studies can direct us towards effective observational and experimental studies. The results of the OSSEs can lead us to better benchmarks and forecasting systems, including the data for forecasts. As the carbon cycle community is increasingly called upon to inform policy, OSSEs are invaluable in terms of directing where and when measurements should be made, in a cost-effective manner, and can contribute toward operationalizing observing systems with improved forecast and predictive skill.

3.4.4 Feedbacks and processes

The way in which processes are represented in models contributes to nearly 80% of the uncertainty in carbon cycle projections (Bonan and Doney 2018). Several large-scale terrestrial processes strongly control the fate of large carbon stores or fluxes, including land use change and land management, nitrogen and water limitation, large-scale releases of soil carbon through permafrost thaw and soil degradation, and disturbances from fire and insects. Model representation of carbon-cycle processes is often based on smaller-scale measurements. For example, leaf-level photosynthesis is scaled to global gross primary productivity and constitutes the largest flux of carbon into terrestrial ecosystems. Although many models use a Farquhar calculation for leaf-level photosynthesis, the manner in which this leaf-level process is scaled to a plant, canopy, ecosystem, and continent varies widely across models (Rogers et al. 2017). Thus, while many key processes regulating the carbon cycle have already been incorporated into most models, the manner in which they are represented differs.

Model estimates of soil carbon pools vary widely, and observations to evaluate soil carbon pools (Fischer et al. 2008) are limited. Global rates of heterotrophic respiration are considerably larger than fossil fuel emissions (~10 Pg C yr^{-1}), but are highly uncertain, with estimates varying from 33 to more than 50 Pg C yr^{-1} (e.g., Hashimoto et al. 2015, Konings et al 2019, Ciais et al., 2020). In models, too, these rates are a dominant source of carbon cycle uncertainty. The ways in which modeled heterotrophic respiration responds to environmental changes, as well as feeds back to soil nutrient availability, play a crucial yet largely unconstrained role in modeled carbon cycle responses. For example, permafrost thaw with climate warming is releasing significant amounts of carbon and mineralizing nitrogen for plant growth (Schuur et al 2015; Koven et al. 2015). The representation of decomposition in models often includes one or more pools of carbon with rates scaled by abiotic factors and the recalcitrance of the carbon in that pool (e.g., Bonan et al, 2013; Koven et al. 2013). More recently, the importance of biological processes has been highlighted with the emergence of several microbial-explicit models (e.g., Wieder et al. 2013).

Fluxes of carbon into terrestrial ecosystems are largely governed by plant physiological processes, with terrestrial vegetation carbon pools dependent upon gross rates of photosynthesis and autotrophic respiration. Although extensive research has led to the development of widely accepted models of photosynthesis, there is still considerable uncertainty in the representation of photosynthesis in models that arises from leaf-level implementation and scaling (Rogers et al. 2017; Lombardozzi et al. 2018) as well as imperfect knowledge of responses to environmental variables (Lombardozzi et al. 2015; Smith and Dukes 2012; Slot and Winter 2017). Similarly, the representation of autotrophic respiration, including maintenance and growth respiration, is quite simplistic. For example, models of respiration often include a static temperature response even though available data suggest some acclimation to growth temperature. When incorporated into process models, respiratory temperature acclimation can have a large impact on terrestrial carbon storage (Lombardozzi et al. 2015).

Process representation of the carbon cycle is often based on smaller-scale measurements (for example, leaf-level photosynthesis to global GPP). We recommend additional research to determine how uncertainty propagates as processes are scaled across space and levels of biological hierarchy. Different factors or processes come into play at different scales, and there are “scale transitions” when the system passes from a scale at which it is primarily influenced by one process to a scale at which it is primarily influenced by a different process. Scaling uncertainty can be evaluated through benchmarking and model validation activities with coordinated prognostic carbon cycle model evaluation, taking into account both complexity and performance as a function of complexity.

NACP science should seek to reduce the uncertainty caused by process representation in terrestrial biosphere models, by evaluating and improving the representation of processes important for carbon cycle prediction. Tools for prioritizing research on processes could be useful for groups conducting empirical and modeling research. While some progress has been made on identifying sources of uncertainty within individual terrestrial biosphere models (e.g., Booth et al. 2012, Dietze et al. 2014) and within photosynthesis models (e.g., Dietze et al. 2013; Rogers et al. 2017), these analyses omit larger-scale processes and those that are not yet included in models. NACP science should target understanding the magnitude of uncertainty caused by model process representation, including evaluating and improving mechanistic representations of these and other processes important for carbon cycle prediction. Additionally, measurement campaigns should target understanding key mechanisms contributing to representation uncertainty. These activities would help prioritize future scientific activity to reduce the greatest uncertainties in large-scale carbon-climate feedbacks.

3.4.5 Focus Areas (Coupled human-natural systems and Land-Ocean-Aquatic Continuum)

In addition to predicting the indirect effects of humans on the carbon cycle from climate change and changes in atmospheric CO_2 and ozone etc., human activities include direct effects such as burning of fossil fuels, deforestation, silviculture, agriculture, marine management, land development (i.e., drainage), and land fragmentation and abandonment. The human systems and natural ecosystems influence one another in ways that our current observing systems and models are not currently designed to understand dynamically. Predicting the drivers and impacts of human-related activities requires taking into account existing infrastructure and investment lifetimes (i.e., 'carbon lock-in') and developing socio-economic scenarios of population growth and economic development. At short time scales (decadal), empirical models relating climate teleconnections, existing land cover and land use, and economic projections can be effective in predicting where land cover transitions may take place (Seto et al. 2012), and are important in the context of shorter-term monitoring of the carbon budget (Le Quéré et al. 2018). At longer-term scales (i.e., centennial), tools like Integrated Assessment Models allow exploration of a range of population and economic growth scenarios coupled with policy and radiative forcing assumptions, similar to those used in the IPCC process (e.g. O'Neil et al. 2017). Up to now, much of the socio-economic and human integration with carbon cycle modeling has taken place in an offline approach, for example, where land cover and land-use change scenarios are provided as diagnostic inputs to models (Hurtt et al. 2020). There is a need to more comprehensively couple human-drivers, including energy consumption and type choices, ecosystem management decisions, infrastructure efficiency, socioeconomics, and agricultural and urban development preferences, into carbon cycle models to effectively constrain feedbacks between the Earth system and human activities (see, e.g., Woodard et al. 2018), particularly as carbon management and geoengineering technologies are proposed as climate mitigation solutions, i.e., biomass energy with carbon capture and storage (BECCS) (Fuss et al. 2018).

Emissions from the burning of fossil fuels are the primary cause of increasing atmospheric CO_2 levels (Friedlingstein et al., 2019), and these fuels have supplied ~85% of primary energy used worldwide in recent years (IEA, 2018). Although inventories of fossil emissions based on energy statistics are regularly published (Andres et al., 2012), little research effort to date has focused on predicting future fossil emissions or their spatial patterns in the context of population, lifestyle, and development trajectories. Energy forecasts are more common, but are notoriously unreliable, particularly in anticipating sudden economic changes or technological breakthroughs (Sherwin et al., 2018; Davis, 2018). Research aiming to predict emissions or even report emissions in near real-time is thus focused on improving the detail and currency of energy data and the techno-economic and weather-related factors that affect energy demand, as well as advances in data science to develop more accurate models. Promising sources of data include satellite observations of nightlights, ship traffic, aerosol concentrations (e.g., NO_x and SO_2), ozone measurements, and energy infrastructure, as well as country- and region-specific economic indicators of consumption, international trade, and industrial activity. Many of our most promising opportunities for emissions mitigation are at local, city-scales; thus granular activity data are needed to identify specific opportunities and assess the efficacy of mitigation efforts (Gurney et al. 2015; Gately and Hutyra 2017).

Prediction of land-use change emissions is similarly rare, again limited by the currency and detail of available information. The emissions impacts of land use changes can extend for decades as land cover can change repeatedly (e.g. forest converted to agriculture and then secondary regrowing forest) and has cascading impacts on the surrounding built and natural ecosystems. Satellite observations of land cover and land transitions gradients represents an increasingly promising source of data which may be used to improve either rule-based predictive approaches such as cellular automata and simple Markov models or more sophisticated, economic-based land-use models that assess the relationship among land-use allocations and the inherent productivity of the land as determined by biophysical features, returns to improvement of the land, society's preferences for various goods, and policies that manipulate economic returns (see, e.g., Radeloff et al., 2012).

Lateral carbon fluxes related to the land-ocean-aquatic continuum (LOAC) represent another focus area for predictive modeling. The LOAC accounts for inland water fluxes of CO_2 and CH_4, the transport of dissolved organic and inorganic carbon from headwaters to estuaries, and the fluxes of estuarine carbon to continental shelves and open ocean. Annually, and at global scales, these fluxes amount to >1 Pg C yr^{-1} and regionally, the LOAC fluxes partly resolve bottom-up and top-down differences in carbon accounting (Kondo et al. 2020, Hayes et al., 2012), and are important components of wetland restoration and climate mitigation. With changes in climate, atmosphere CO_2, and land-use and land-cover change, LOAC fluxes will likely be significantly altered. Current methodologies to estimate LOAC fluxes remain highly empirical, i.e., scaling fluxes made at the chamber scale by remote-sensing based areal estimates. This approach presents challenges for predictive modeling, especially when environmental conditions are changing. We recommend an emphasis on process-modeling approaches to represent LOAC fluxes and that these approaches provide the basis for predictive modeling of LOAC at seasonal, decadal, and centennial time scales.

Key Priorities:

Systematic improvement in prediction of how ecosystems will respond to global change in the near and long term can be achieved with an emphasis on the following:

1. ***Comparison between model predictions vs. observations** of the system, in all its forms and with a regular cadence, including model evaluation through use of hindcasts and retrospective analyses, the incorporation of data assimilation techniques in model development, application, and evaluation, a regular practice of iterative near-term forecasting, and comprehensive end-to-end uncertainty quantification.*
2. *The **establishment of community-wide benchmarks for model evaluation**, i.e., reference data sets, methods, and model performance metrics. This includes incorporating data from global-change experiments into benchmark datasets, and consideration of multiple metrics of model performance.*
3. ***The use of Observing System Simulation Experiments (OSSE's)** to systematically evaluate our existing systems for observing the carbon cycle and its dynamics, and identify what data would need to be collected to improve prediction.*
4. ***The development of process models that better capture key aspects of complexity**, e.g., non-linearities in the environmental sensitivity of key ecological processes, and feedbacks operating at spatial and biological scales in between the leaf and the global scale.*
5. *Attention to **new focal areas** requiring advances for improved prediction, including the influence of social systems as drivers, and neglected ecosystem processes, such as lateral fluxes and terrestrial-aquatic flows.*

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Chapter 3.5: Communication, Coordination and Decision Support

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One of the leading goals of NACP is to facilitate clear and effective communication of current understandings of how the carbon cycle is responding to contemporary forcings to reach diverse audiences including non-specialists. In addition, the NACP seeks to develop decision support tools that aid private sector and public sector decision makers as they explore the changing carbon cycle, including human-induced greenhouse gas emissions, and as they consider impacts of a range of policy and management actions. To achieve these aims the NACP needs to translate and apply scientific understandings and evidence into formats that are accessible, relevant, credible and useful for decision makers, and the general public, at local, state and national scales. Success in these areas would bridge from research-focused activities to practical application by society as well as to education and outreach (Figure 3.5.1).

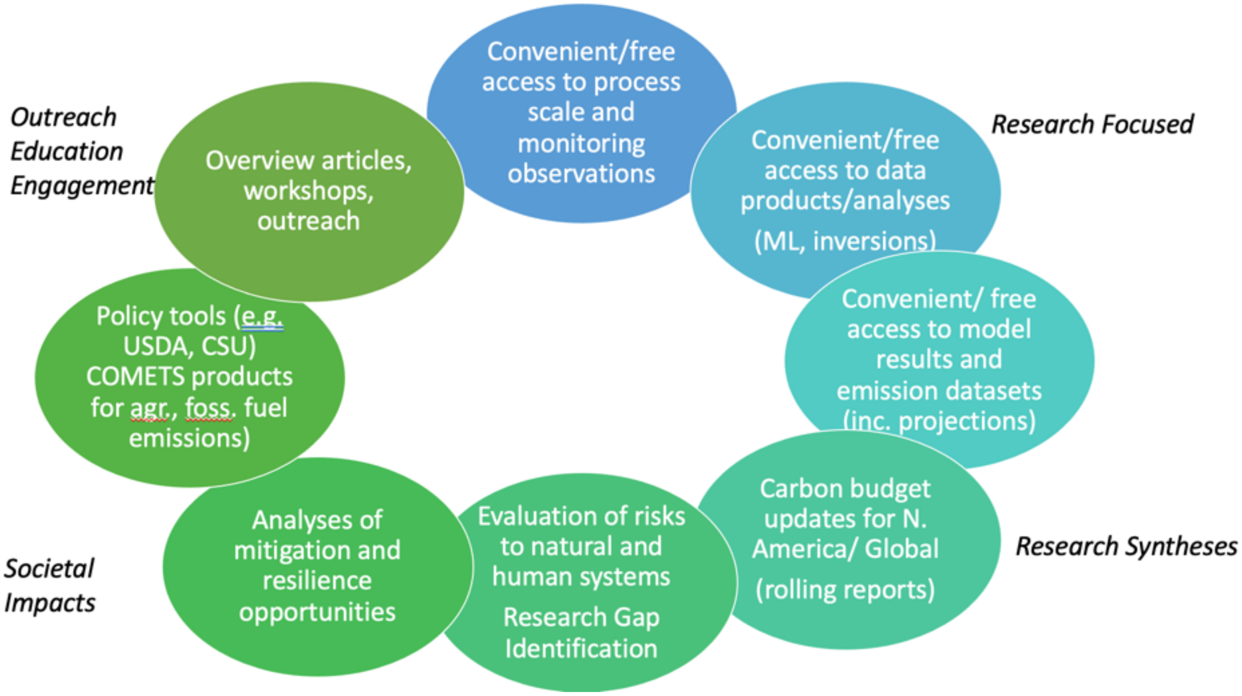


Figure 3.5.1. Constellation of Activities Bridging Carbon Cycle Research to Applications and Use in Society.

3.5.1 Communications Goals

The NACP, along with the rest of the scientific community, has worked over the past decades to improve communication with policymakers, with a goal of informing sound public policy decision-making. Examples of institutions and individual scientists providing timely, appropriate, and high-quality information to Congress and government agencies can be drawn from public health, food availability and safety, and environmental management, as well as research and science education policy. On the topic of climate mitigation, land use, and environmental regulations, however, less progress has been made (Funk et al. 2015).

High-quality scientific information is needed by those envisioning solutions to many of the significant problems facing humanity. Research needs to provide the relevant information and scientific understanding needed to make wise policy decisions. To ensure support for this research and its use, the NACP must appropriately and effectively share its knowledge through the development of social media platforms, news organizations and monitoring systems, as is described in the last section of this chapter and throughout. How knowledge is shared will vary according to the potential uses, from the individual to the institution, from local decisions about a single tree to regulatory frameworks affecting entire countries (Cohen et al. 2014). How knowledge is shared also will vary according to the audience, recognizing that effective communication relies on an audience that values the information — and that internalizes it to some degree. NACP has a role to play in maintaining and elevating public value of the benefits of its science, in part to support adequate funding of the community's important work, and also so that its expertise and insights are used in practice, ensuring that decisions are made with the best available information rather than simply whatever information might be at hand (Gropp 2018).

We recommend a focus on three communications goals for the NACP in the coming decades, emphasizing the need to reduce information barriers for decision makers, to improve understanding of uncertainties, and to help to advance the science of communicating science.

3.5.1.1 Reduce Information Access Barriers for Decision Makers

The NACP should work to address barriers to policy-relevant information through data-sharing, transparency, and open-access to information via public- and private-sector user-communities. These barriers can include privacy, intellectual property, legal, liability or political concerns. The NACP has as its data policy the 'full, open, and timely sharing of the full suite of North American data sets for all NACP researchers.' Although this policy is in place, it continues to be challenging for researchers to comply with due to the need for datasets to be 'final', cleaned, searchable, referenced, and complete, something that for many datasets could take years to achieve.

However, it could be that information is shared, but policy makers are unable to use it because the research is not currently formulated in ways compatible with current decision-making models. For example, the National Acid Precipitation Assessment Program ambitiously attempted to develop the science base for a set of critical policy decisions regarding acid rain. According to several retrospective analyses, however, its results were largely ignored by decision makers because they were not timely, clearly connected to policies, and generated with specific policy-related priorities in mind (Jones et al. 1999). Relevant information for a pending policy decision may be available online, in the literature, and widely known, but if the information fails to be communicated in a way that can be accessed by policy makers, it won't be used. Presenting the information is important but scaling of the information to targeted policy makers while also giving a timeline is also crucial. How long will this information be good for? Will the information support the policy in the future as well as now? Answering these questions is central to usability and can be addressed with surveys of various communities and actors in business, government and civil society.

Developing and presenting carbon cycle science research with greater utility for policy makers requires an unprecedented amount of knowledge on the policy context and significant investment in time and resources in supporting decision making. Greater investment by agencies to provide clear, concise, targeted information for specific policies would enhance utilization of research, such as collating research on targets for scientifically defensible thresholds for carbon pricing. Working directly with relevant actors in business, government and civil society to determine what information they need when they need it, and linking this to published research, would help improve the dialogue and utilization of scientific research. Also, by integrating emissions from specific societal activities up to larger scales such as a city or a region, the NACP could improve policy makers' understanding of how policies impact emissions.

Innovative partnerships between researchers, funding entities, and beneficiary actors in business, government and civil society could include public-private partnerships. One example is a relatively new collaboration between Google and the UN Environment division, aiming to track specific environment-related development targets with a user-friendly Google front-end.

A basic review of media accounts indicates a clear need for improved communications about the basic facts of how the carbon cycle is linked to climate change is evident in (Figure 3.5.2), signaling an area in need of attention for NACP and related science communities. Several groups provide examples of how NACP could improve its communications and outreach to have broader impact and reach, such as the Global Carbon Project, the Long Term Ecological Research (LTER) program, NASA's Earth Observing System (EOS), National Ecological Observatory Network (NEON), the Ocean Carbon & Biogeochemistry Program. The NACP could improve its engagement with high profile organizations with access to government and public policy decision makers. Social media (e.g. Facebook, LinkedIn) and print media (New York Times, Washington Post, etc.) organizations and outlets could be better leveraged by NACP scientists to communicate broad findings to a wide spectrum of interested parties.

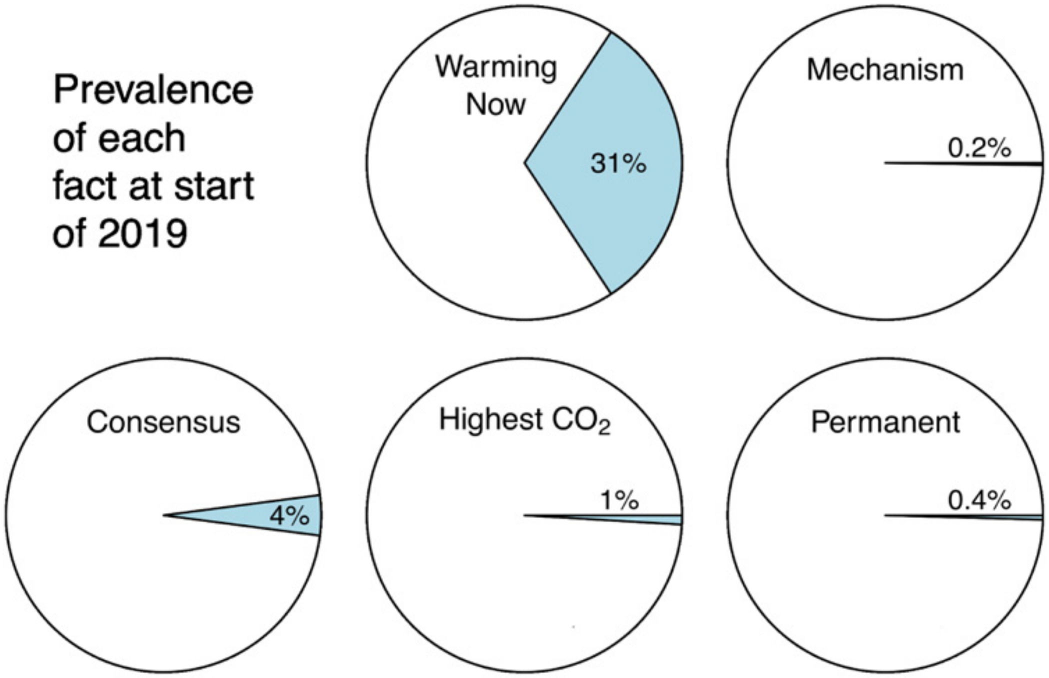


Figure 3.5.2. Media Mentions Indicate an Enduring Need to Elevate Communications About Carbon Emissions and Climate Change. Shown is the percentage of climate change articles in the New York Times since 1980 that mentioned five basic facts about global warming: the climate is warming now, the mechanism is through the burning of fossil fuels, there is strong scientific consensus about those facts, there is more CO_2 in the atmosphere than there has been for hundreds of thousands of years, and that these changes are effectively permanent. (Graphic by David Romps, UC Berkeley, from Romps and Retzinger 2019).

The diverse community of actors in business, government and civil society are both providers of bottom-up information relevant to carbon cycling and also users of that information. NACP could consider hosting a data portal that would allow major private corporations and cities to upload data relevant to documenting and analyzing their carbon footprints, providing insights into their emissions portfolio and allowing them to compare results with other corporations, cities and industries, or to assess how their operations contribute to national accounts. Also, NACP can facilitate communications among these actors by integrating the information they provide in a shared frame of reference.

Another aspect of reducing barriers is the encouragement of funding, publishing and academic programs that reduce ‘silos’ and improve NACP scientists’ engagement in decision support and communication activities. Incentivization of service and education activities for this community means providing funding support and highly visible prestige to scientists who spend their time engaging with decision makers. Scientists may need training in how to constructively engage with decision makers. For scientists, there often are similar communication barriers with policy makers as there are with media and the public.

By encouraging, rewarding, and facilitating 'user engagement' from the start of new research projects, and encouraging scientists to make carbon cycle observations, models and tools that are directed toward practical applications, the NACP can reduce barriers to scientists' participation in outreach and engagement, and simultaneously elevate incentives for outside actors to engage with the scientist community.

3.5.1.2 Uncertainty in carbon knowledge and its communication to, and application by, decision makers

Whereas past efforts have achieved significant advances in producing and communicating detailed inventories, observations, and model projections, future efforts require a systems-approach to provide actionable information for decision making with clear communication about uncertainties. The way uncertainty is communicated can have systematic effects on decision making around government policy, corporate investment, economic growth, and consumer behavior, but these relationships are poorly understood. Communicating information and data with confidence estimates in both space and time allow for immediate understanding of the certainty of outcomes across both observations and models. Even the term "uncertainty" itself tends to lead to distrust of information and can lead to inaction. Focusing on confidence estimates, as opposed to uncertainties, can shift the perception of the discussion from something of weakness to a topic of strength and optimism.

The NACP needs to create a communications strategy which is focused on the continual need to revisit, understand, and define how carbon cycle science findings are understood and used by decision makers and other societal actors. Focusing on how confident the developer is, with clearly explained and visualized data, is critical for effective communication. Visual representations of probabilistic events are often misinterpreted by the general public and by policy makers. Although various uncertainty visualizations are now in use, the parameters that determine their successful deployment are still unknown and require more research to be effectively implemented (Tak et al., 2015). For example, uncertainty and error bars are seen as too technical and are not relatable for many decision makers. This is an immediate deterrent as they feel the information is not tailored to them. Carbon cycle scientists should consider engaging with scientific expertise from psychology, engineering and political science, among other disciplines, to effectively communicate their uncertainty information.

3.5.1.3 Participate in the science of communicating science

NACP needs to learn from the broader scientific community that is engaged in studying the most effective ways of communicating science with policy makers, private institutions, the public, and others. Communication approaches need to be adapted to reflect the circumstances around which the information is being imparted and the goals of the communication. There is a growing literature and expertise that can be drawn upon that can help inform the most effective ways of communicating with the public and with non-expert audiences, through a variety of outlets like social media (National Academies of Sciences, Engineering, and Medicine, 2017). By clarifying the NACP's goals for communicating with different audiences within different contexts, the strategy taken will vary. The NACP should engage with science communicators and social scientists researching the complex individual and social phenomena that impede or enhance science communication.

The NACP should engage with social scientists to identify process-level understanding of human factors that determine carbon emissions from energy use, industrial activities, transportation and others to increase relevance of carbon cycle science. The challenge is not only in understanding how policy makers at various levels and the public interpret available science, but also understanding how carbon cycle science can be more accessible and relevant to individual and collective decision making. In addition, the NACP should confront the challenge posed by *intentional* dissemination of misinformation about climate change and efforts to undermine trust in scientific and governmental institutions.

The domain of the NACP is to study the sources and sinks of carbon with the expectation that resulting knowledge should ultimately be accessible and salient to societal actors at a variety of levels. Although scientific research does not have a simple cause-and-effect relationship with improved societal outcomes, as one example, research has led to policies seeking to reduce society's exposure to extreme events (Rosenzweig et al. 2014). Although it is a goal of the NACP to improve communication of carbon cycle research to decision makers, to do this it is necessary that natural sciences be integrated with the study of human processes. However, the integration of social and human aspects in carbon science is challenged by the need for translation and cooperation between different kinds of user communities. Researchers tend to interact more closely and share similar technical language with other researchers in their own fields, which can frustrate interdisciplinary cooperation amongst those who study natural sciences, social sciences, and economics.

Key Priorities for Communication:

1. *Rewarding NACP scientists for engagement with user communities and societal actors early in the research process.*
2. *Investment in new capabilities in uncertainty communication and interdisciplinary work to visualize effectively how certain models, processes and outcomes are for a diversity of audiences.*
3. *NACP institutional engagement across multiple social science and physical science disciplines to ensure that scientific outputs are able to provide joint representation of natural and managed systems that can be communicated to user groups.*
4. *Facilitate communications among societal actors by placing carbon information within a shared frame of reference.*

3.5.2 Decision Support Goals

The readiness of decision makers to receive climate information varies widely, from those who do not consider climate in any decisions to those who are entirely focused on adaptation and mitigation. The NACP should engage its community in developing flexible, customizable tools that allow users to access appropriate scientific information which is understandable even for those with only a basic knowledge of the subject and with a range of pathways for approaching information. Of specific interest and need are decision support tools for informing carbon management being considered and performed by diverse actors in society.

3.5.2.1 Engagement with boundary organizations to co-produce knowledge

Public policy and decision making rely on expertise and expert knowledge but that knowledge does not always flow naturally from source to user. Boundary organizations can facilitate a science-policy and science-management interaction that is dynamic and collaborative. Science from the NACP contributes to rules, regulations, and legislation but also to decisions made by environmental managers and industry at a variety of scales as they interpret and implement policies. By engaging with boundary organizations at a variety of scales, the NACP can facilitate multidisciplinary research and the interaction and engagement with policy makers in the local, regional, national and international arenas.

Boundary organizations can facilitate the interactions between science producers and users, enabling the NACP to ensure that scientists are able to provide essential information to decision makers while continuing to focus on their own science and expertise. Guston defines a boundary organization using three criteria:

- The organizations provide the opportunity and sometimes the incentives for the creation and use of boundary objects and standardized packages;
- They involve the participation of actors from both sides of the boundary, as well as professionals who serve a mediating role; and
- They exist at the frontier of the two relatively different social worlds of politics and science, but they have distinct lines of accountability to each (Guston, 2001).

By facilitating the communication between its scientists and organizations making decisions such as regulators or businesses, the NACP can contribute to the increased uptake of the science and improve the relevance of the data products and science that the NACP members create. This engagement ensures the accurate identification of decision makers and the information they need to make better decisions, along with the design of the best possible scientific data products and communication systems to deliver the information decision makers require.

Examples of effective boundary institutions include the Decision Center for a Desert City, located at Arizona State University, which focuses on developing fundamental knowledge about decision making from three interdisciplinary perspectives: climatic uncertainties, urban-system dynamics, and adaptation decisions. The Decision Center has worked with Phoenix communities to implement sustainable development goals and increase equity, sustainability and resilience in a desert city (Sachs et al., 2019; Stanley, 2017). Another example is the use of sea level rise information in climate adaptation measures taken in urban areas. The New York City Panel on Climate Change is a New York City Mayor-appointed advisory board of researchers who act as a boundary organization, guiding the infrastructure and adaptation investments in the New York and New Jersey Port Authority (Mills-Knapp et al., 2011). These changes have resulted in increases in property values, particularly in areas proximate to hard infrastructure, green infrastructure, and building structural elevation projects (Kim, 2020).

Two additional examples are given below. Both involve boundary organizations who have been directly involved in producing science or have been collaborators on grants and research. Molly Macauley of Resources for the Future (RFF) collaborated on projects and grants with a variety of NACP scientists since 2009, and therefore had a hand in focusing efforts of scientists and their use of remote sensing data in models to ensure their relevance to decision making.

Example 1: Resources for the Future engagement with forest regulations for carbon sequestration

In the United States, forests store the equivalent of 52 years' worth of US carbon emissions. This reservoir is expanding by about 0.5 percent per year; however, net growth is expected to decline over the next 30 years, primarily due to land use changes and forests aging. In order to mitigate this decline and expand carbon storage in forests, the Obama-era Mid-century Strategy for Deep Decarbonization proposed a set of policy options, including afforestation (creating new forests), avoided deforestation, and by implementing forest management strategies. **The boundary organization Resources For the Future (RFF)** is working to determine the amount of carbon forests may sequester and the potential effectiveness of the policy. RFF is also working directly with satellite remote sensing scientists and modelers to determine the impact of different forest policies and emissions from forest harvest, notably using high resolution forest maps generated by Huang et al. (2019). By evaluating potential and existing policies using data and information generated by the NACP, RFF can directly influence future policies of the United States.

Example 2: Finite Carbon and Forest Offsets

The boundary organization Finite Carbon Corporation has worked with a wide variety of landowners and corporations to create forest reserves that can generate revenue from the protection, restoration and sustainable management of forests. By putting a price on carbon, the organization allows for carbon emitters to invest in forest conservation and reduce their impact on the environment. Finite Carbon has recently been acquired by oil giant BP in their efforts to diversify their sustainability offerings and accelerate their net-zero goals.

Finite Carbon works to increase the ability of the forest management community to scale-up the infrastructure needed to quantify, monitor and verify the carbon sequestered in forests in the United States. As of 2021, the corporation has 50 carbon projects on three million acres in the US and is working to extend this effort to new geographies. By aggregating forest plots as small as 40 acres together, the organization will enable small landowners to access the carbon offset market, reducing barriers including high transaction and reporting costs. Through use of systematically applied modeling, verification and monitoring, the corporation is working to ensure that the carbon sequestered through its efforts delivers long-term results.

By supporting the engagement of scientists with policy makers, decision makers and others who may use their science, the NACP can help demonstrate the value of investing in research that explicitly aims for the co-production of knowledge. Co-production of knowledge, by identifying the demands of a consumer of information and by working with information users from the start of the scientific process, allows scientists to develop results that are both usable and socially robust. Also, it contributes to users being more engaged in and invested in the science. User-driven science thrives when institutions shift priorities to meet user needs and set reward structures accordingly. To that end, the NACP could promote intentional inclusion of communications as a priority element of research agendas, project plans, and community initiatives, as well as identify leading objectives for communicating the community's findings to reach specific institutions and actors and to achieve select objectives.

When scientists communicate useful information more effectively to decision makers, science thrives. Science is increasingly interdisciplinary, which fosters collaboration and innovation. Being able to communicate the relevance and impact of their ideas and discoveries can enhance scientists' ability to secure funding or find a job. It allows them to write better and more comprehensible research papers and to utilize more relevant communication tools. It also allows them to be better teachers and mentors for next-generation scientists. There needs to be a stronger emphasis on the information handoff and knowledge continuity during research programs if we are to ever bridge the gap between science and policy. This takes significant effort and time, which needs to be included in grants and proposal opportunities provided by funders. The NACP can inform these agencies on the importance of including science communication in their funding of scientific endeavors.

3.5.2.2 Reducing Barriers to Access for Decision Makers

The scientific community should prioritize engagement with frameworks and boundary institutions early in their research process to accelerate and enhance their individual efforts in working with policy makers. Carbon cycle science will require improved interaction and information exchange not only within and among different scientific disciplines, but also with actors in business, government and civil society. These groups require up-to-date assessments, improved approaches for understanding complex and interdependent issues, and ways of quantifying and dealing with uncertainty (West et al., 2018). There is a need to bridge the differences between the research results published by scientists and the information needed to make decisions regarding policy and regulation – to translate research findings into meaningful input for these groups. This work can be done through boundary organizations that can ensure a sustained and ongoing dialogue among the different groups to raise awareness of both what science can provide and what science cannot provide, and of the uncertainties associated with current assessments and projections of the future (Michalak et al., 2011).

In order to engage decision makers, mapping and visualization of carbon flows is required to help institutions and individuals involved in investment, production, consumption, management, and policy making to visualize how their processes substantially impact the carbon cycle. Interconnectedness of carbon flows among societal actors should be illustrated. This can help to reveal their direct and indirect emissions, constraints and incentives surrounding their behavioral decisions, ability to create change in other actors through regulatory mandates, persuasion, purchasing choices, specific decisions and information needs for those decisions, the timeline of decisions, and the precision, authoritativeness, and latency requirements placed on that information. Boundary organizations do this knowledge mapping and provide sustained engagement with these institutions and decision makers, which will improve the ability of NACP scientists to make an impact.

For example, investment in energy infrastructure in rapidly growing urban areas should take into account a wide variety of information which will help policy makers set up the investment and appropriately size the infrastructure according to the economic, demographic and technology projections of the area being served. Scientists can contribute to providing information to the decision making, but instead of attempting to work with each individual organization they may achieve greater impact and efficiency by working through a boundary organization.

An example of an institution that engages with policy in Canada is Ouranos, which is self-described as an “innovation cluster and consultation forum enabling Quebec society to better adapt to climate change”. They are effective knowledge translators for key industries on climate change and carbon emissions reduction. For over 15 years, Ouranos has been providing climate information to regional and national clients, helping them identify and implement climate change adaptation strategies and improve regulation and decision making in government. A US national-level boundary organization is the Consortium for Science, Policy and Outcomes (CSPO) that focuses on translating science for the government across multiple disciplines. They do research on policy for science (how we nurture the health of the research enterprise) and science for policy (how we use knowledge more effectively to achieve social goals).

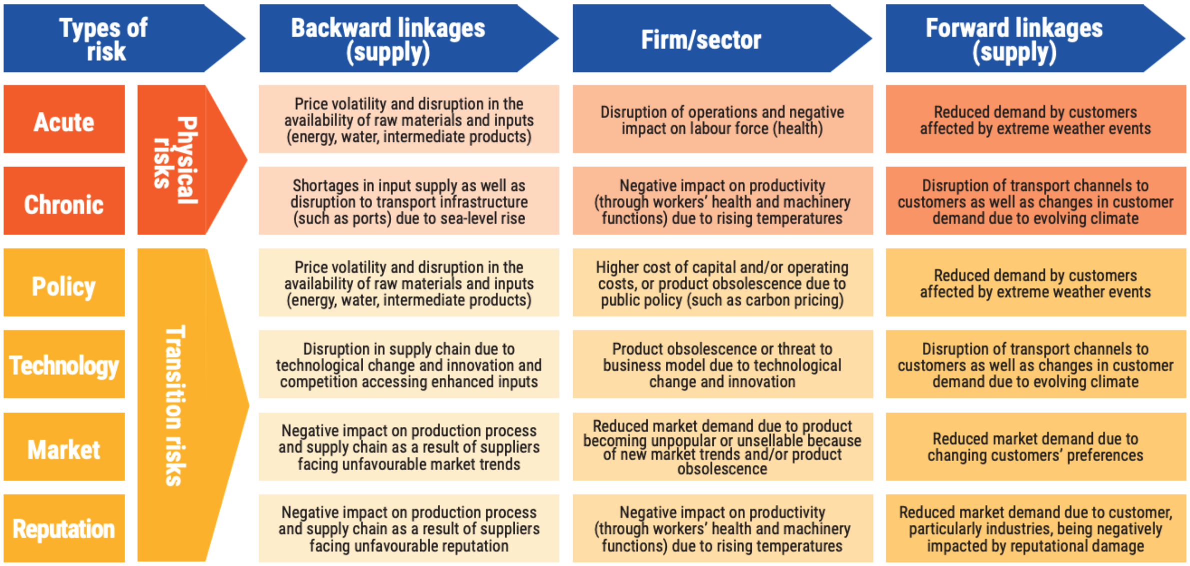
3.5.2.3 Delivering Relevant, Credible, and Legitimate Outputs

As part of the idea of co-production of knowledge, scientists have been encouraged to 'address decision maker needs for current and future carbon cycle information and provide data and projections that are relevant, credible, and legitimate for their decisions' (Goal 6, US Carbon Cycle Science Plan, 2011). To do this, scientists must be sufficiently aware of the needs of decision makers and be working in an area that is able to create sufficiently accurate, relevant science results.

Part of being relevant and responsive to decision maker needs is being able to define who the decision maker is that the research is addressing. What aspect of the carbon cycle do these decision makers work on, and which are affected by particular decisions (sinks, sources, stocks, flows)? What information do the decision makers need, get, and act upon? Clearly identifying the deficits in the information at each level of decision-making, and the participating actors, is a clear first step in designing relevant carbon research. Mapping information and capabilities of the NACP community to the needs of users will allow production of information in formats and timing that align with standard practices for a variety of decision makers.

Another essential part of this goal is to establish a shared vision of what knowledge is usable in decision processes. For example, how can data, models and observations provide critical information about the 'extreme' upper tail of climate response and threatened damage due to carbon emissions, linking improved understanding, observations and models of carbon processes to the urgency for action. Just writing papers about these extreme responses may be insufficient to engender a response – we must understand the usability of data, research and information within decision making processes.

One of the most relevant research outputs is information regarding carbon emissions and offsets within the supply chain. A key element is to understand the risk landscape faced by business (Figure 3.5.3). Most private organizations choose to mitigate emissions indirectly by investing in offsets within their supply chains, or in partnership with carbon credit markets. Indirect emissions, supply chain emissions, and offset research and data is therefore a priority- including specifically data regarding Scope 1 or direct emissions such as from vehicles owned by the firm or direct consumption of energy while doing business, Scope 2 or indirect emissions such as from purchased electricity, and Scope 3 emissions, which include other indirect emissions such as employee travel, waste disposal, production of purchased materials, use of products and purchased services that emit greenhouse gases.



Types of risk		Backward linkages (supply)	Firm/sector	Forward linkages (supply)
Acute	Physical risks	Price volatility and disruption in the availability of raw materials and inputs (energy, water, intermediate products)	Disruption of operations and negative impact on labour force (health)	Reduced demand by customers affected by extreme weather events
Chronic		Shortages in input supply as well as disruption to transport infrastructure (such as ports) due to sea-level rise	Negative impact on productivity (through workers' health and machinery functions) due to rising temperatures	Disruption of transport channels to customers as well as changes in customer demand due to evolving climate
Policy	Transition risks	Price volatility and disruption in the availability of raw materials and inputs (energy, water, intermediate products)	Higher cost of capital and/or operating costs, or product obsolescence due to public policy (such as carbon pricing)	Reduced demand by customers affected by extreme weather events
Technology		Disruption in supply chain due to technological change and innovation and competition accessing enhanced inputs	Product obsolescence or threat to business model due to technological change and innovation	Disruption of transport channels to customers as well as changes in customer demand due to evolving climate
Market		Negative impact on production process and supply chain as a result of suppliers facing unfavourable market trends	Reduced market demand due to product becoming unpopular or unsellable because of new market trends and/or product obsolescence	Reduced market demand due to changing customers' preferences
Reputation		Negative impact on production process and supply chain as a result of suppliers facing unfavourable reputation	Negative impact on productivity (through workers' health and machinery functions) due to rising temperatures	Reduced market demand due to customer, particularly industries, being negatively impacted by reputational damage

Figure 3.5.3. Climate Risks Faced by Business. There are a variety of risks, both physical and transitional, that small and medium sized businesses face due to the changing climate. These involve supply chain as well as direct threats to business functioning via demand and distribution impacts. [Figure reproduced from Montmasson-Clair (2019)]

Having clear guidance and description of the data needs of potential users of carbon cycle science could allow a standardization of format, resolution, latency and continuity of data for decision makers across a variety of organizations. For example, NASA provides low-latency datasets by creating a parallel processing stream that reduces the time between the satellite observation and the issuing of the product to meet decision making requirements. One key difference between low latency and standard data products is that low latency geolocation may not be as accurate because the standard products use the best knowledge of the spacecraft position and attitude which may not be available until after the low latency products are produced (Davies et al., 2017). However, if these products cannot be used if they have a longer latency regardless of their accuracy, they cannot provide the utmost value to society and to decision makers. A similar parallel approach could be taken by NACP scientists so that the format, resolution, latency or necessary continuity of data needed for effective use of their science output is understood and integrated into operational uses. Research funding should incentivize the inclusion of user needs assessments in projects.

3.5.2.4 Decision Support and Monitoring Systems for Carbon Management

The NACP has been focused on developing appropriate scientific foundations for effective communication and support for decision making. The next step in effective support for carbon monitoring is setting up a center where information, data, models and expertise can be available to support actions on carbon management and policy development. This section provides a brief outline of how the NACP could contribute to the development of such a system to support effective policies and leadership on climate mitigation and adaptation.

Here, we define *carbon monitoring* as being focused on sustained measurement or assessment of all carbon dynamics that are needed to estimate total carbon exchange between the biosphere and atmosphere (West et al., 2013). The West et al paper also defines *carbon management* as an effort to manage human activities that alter baseline carbon stocks and fluxes, including fossil fuel production and combustion, land cover change, agriculture or geoengineering of the carbon cycle. To determine the effectiveness of policies, incentives and regulation on emissions, *carbon accounting* includes efforts to reconcile carbon stocks and fluxes across space and time to create seamless estimates that can be used to address the needs of decision makers.

Information and Monitoring for Carbon Management

A decision support system (DSS) is a set of data and models that support decision making across a variety of scales. DSSs serve the management, operational and planning levels of organizations and help people to make decisions about problems that are rapidly changing or that are not easily specified in advance. Because the production of greenhouse gases in the United States is a multi-sector problem (Figure 3.5.4) that includes large scale sources that can be easily identified (such as electricity generation) along with millions of small sources such as residential heating or car emissions that need to be managed using policy or economic mechanisms, a DSS is needed to allow for rapid analysis of impact of policies to ensure that they are effective. The United States does not have decades to determine which set of punitive regulations, financial incentives and policies actually reduce emissions overall. Since ‘my carbon is your carbon’, there is significant danger that some policies may actually increase overall carbon emissions through unintended impacts.

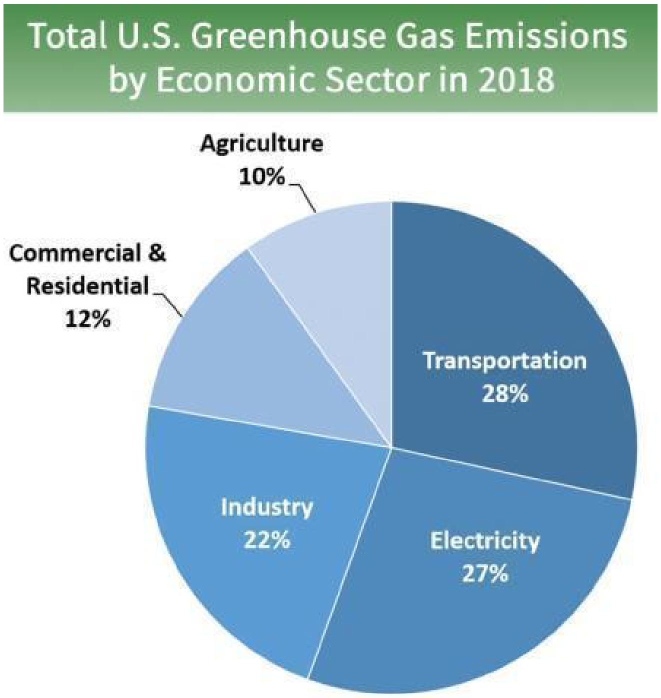
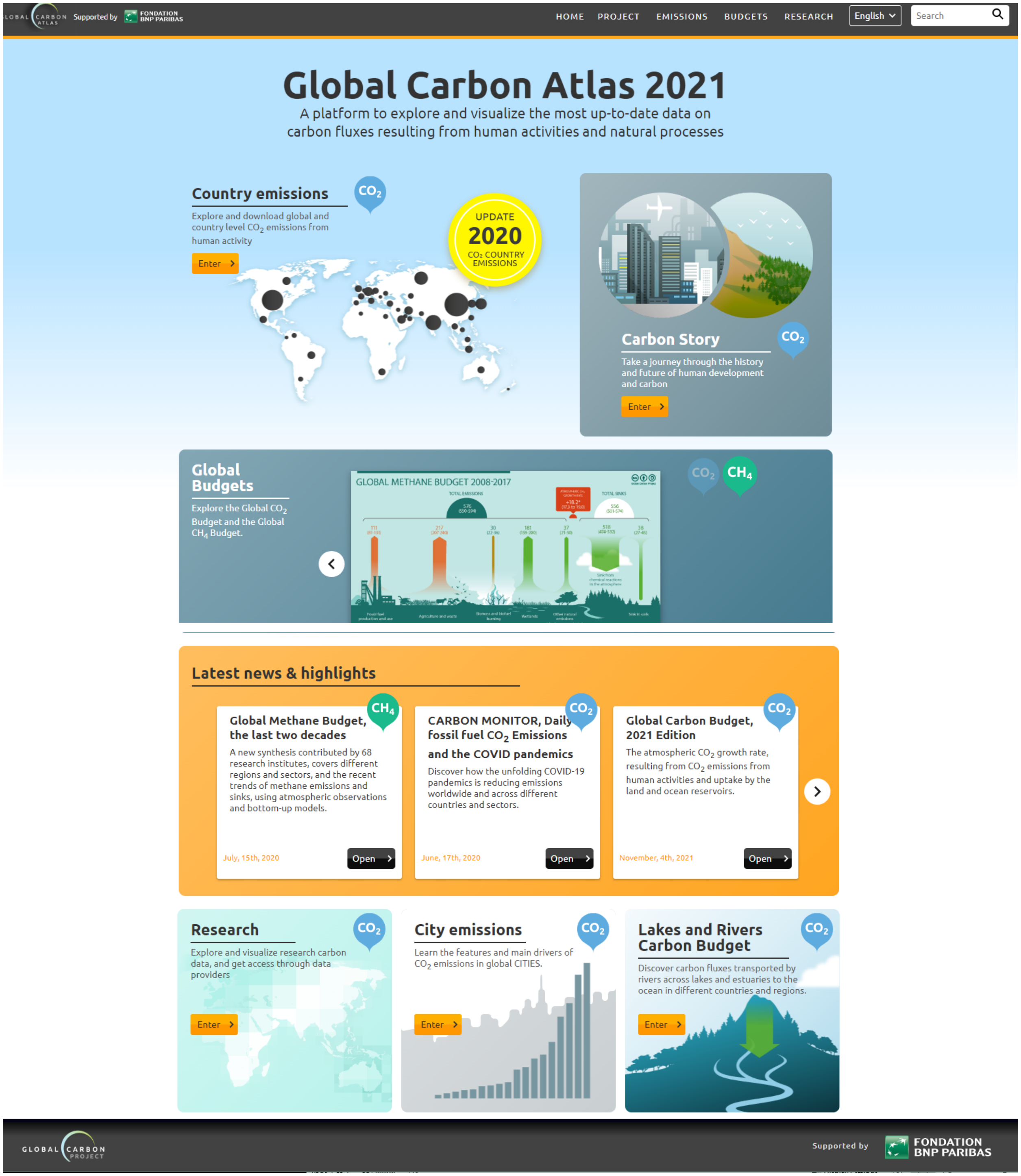


Figure 3.5.4. Sectoral Distribution of Total US Greenhouse Gas Emissions in 2018. Total emissions equaled 6,677 Million Metric Tons of CO_2equivalent. Percentages may not add up to 100% due to independent rounding. Land use, land-use change, and forestry in the United States is a net sink and offsets approximately 12 percent of these greenhouse gas emissions, this emissions offset is not included in the total above. All emission estimates from the US EPA *Inventory of US Greenhouse Gas Emissions and Sinks: 1990–2018.*

Monitoring carbon emissions includes both top down and bottom-up analysis and modeling, and a significant advancement in our ability to attribute carbon emissions to specific sources and sectors. For example, if an incentive was set up for Americans to switch from a petroleum car to an electric car, total emissions of these vehicles must include the mining of raw materials, manufacturing and maintenance of the batteries that they run on, as well as the entire electrical generation system needed to charge them throughout their life cycle. Electric vehicles will be even more effective at reducing emissions from the transportation sector if they are combined with recycling systems to reuse and reduce emissions in the mining sector, and massive reductions in the carbon intensity of the electricity generation sector will be needed. Such a full accounting is needed to ensure that appropriate policies are developed to meet the goal of substantially reduced emissions. This kind of implementation science is beyond what the NACP has typically worked on in the past, but it will be essential for development of appropriate and effective policies.

Two examples illustrate the kind of information and decision support platform that could be emulated and expanded upon by the NACP. The first is the Global Carbon Atlas of the Global Carbon Project (Figure 3.5.5). This platform invites visitors to explore and visualize the most up-to-date data on carbon fluxes resulting from human activities and natural processes. The second example is the US EPA household carbon footprint calculator (Figure 3.5.6). This platform enables visitors to obtain an approximate estimate of their household's carbon footprint based on US average values, with users entering basic data such as zip code, home square footage, vehicle miles per year, and so forth, and allowing them to explore the emissions reductions from selecting alternative technologies or changing their practices.



Global Carbon Atlas 2021

A platform to explore and visualize the most up-to-date data on carbon fluxes resulting from human activities and natural processes

Country emissions

Explore and download global and country level CO_2 emissions from human activity

Carbon Story

Take a journey through the history and future of human development and carbon

Global Budgets

Explore the Global CO_2 Budget and the Global CH_4 Budget.

Latest news & highlights

Global Methane Budget, the last two decades

A new synthesis contributed by 68 research institutes, covers different regions and sectors, and the recent trends of methane emissions and sinks, using atmospheric observations and bottom-up models.

July, 15th, 2020

CARBON MONITOR, Daily fossil fuel CO_2 Emissions and the COVID pandemics

Discover how the unfolding COVID-19 pandemics is reducing emissions worldwide and across different countries and sectors.

June, 17th, 2020

Global Carbon Budget, 2021 Edition

The atmospheric CO_2 growth rate, resulting from CO_2 emissions from human activities and uptake by the land and ocean reservoirs.

November, 4th, 2021

Research

Explore and visualize research carbon data, and get access through data providers

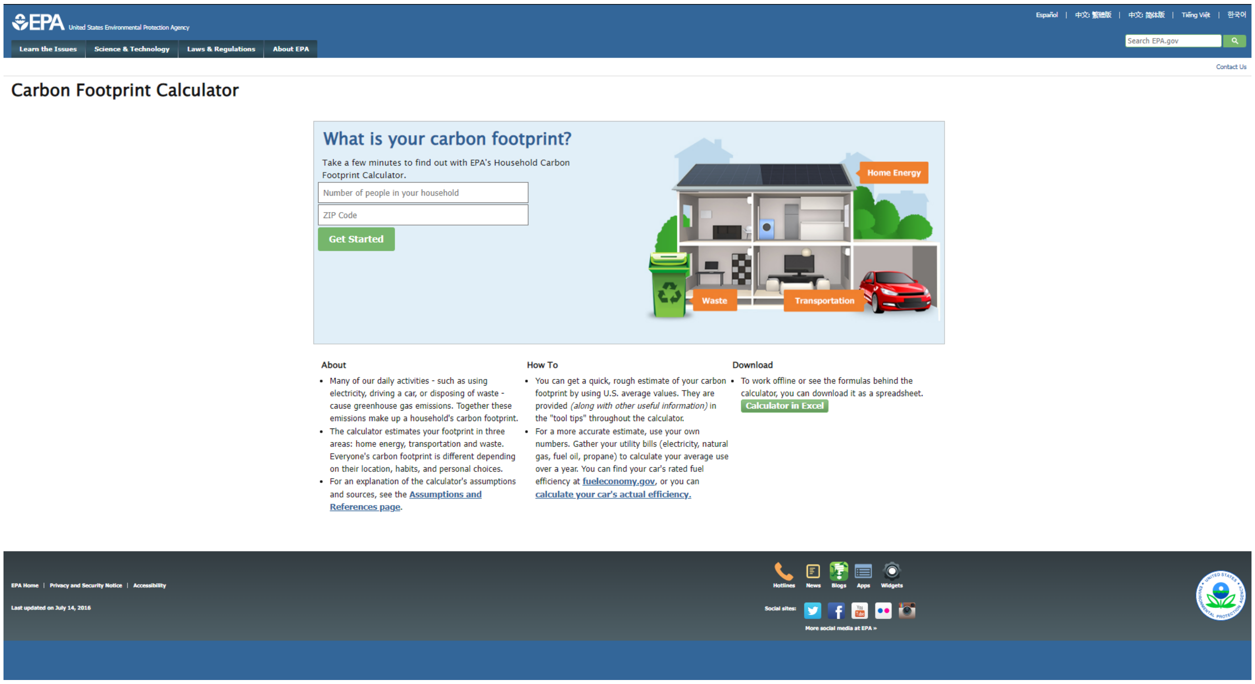
City emissions

Learn the features and main drivers of CO_2 emissions in global CITIES.

Lakes and Rivers Carbon Budget

Discover carbon fluxes transported by rivers across lakes and estuaries to the ocean in different countries and regions.

Figure 3.5.5. Example information platform for elevating awareness of contemporary dynamics of the global carbon cycle, of country scale emissions, and of the coupled carbon-climate system taken from the Global Carbon Atlas of the Global Carbon Program (screen capture from 6/15/2022 at http://www.globalcarbonatlas.org/en/content/welcome-carbon-atlas).



Carbon Footprint Calculator

What is your carbon footprint?

Take a few minutes to find out with EPA's Household Carbon Footprint Calculator.

About

- Many of our daily activities - such as using electricity, driving a car, or disposing of waste - cause greenhouse gas emissions. Together these emissions make up a household's carbon footprint.
- The calculator estimates your footprint in three areas: home energy, transportation and waste. Everyone's carbon footprint is different depending on their location, habits, and personal choices.
- For an explanation of the calculator's assumptions and sources, see the Assumptions and References page.

How To

- You can get a quick, rough estimate of your carbon footprint by using U.S. average values. They are provided *(along with other useful information)* in the "tool tips" throughout the calculator.
- For a more accurate estimate, use your own numbers. Gather your utility bills (electricity, natural gas, fuel oil, propane) to calculate your average use over a year. You can find your car's rated fuel efficiency at fueleconomy.gov, or you can calculate your car's actual efficiency.

Download

- To work offline or see the formulas behind the calculator, you can download it as a spreadsheet.

Last updated on July 14, 2016

Figure 3.5.6. Example information platform for elevating understanding of household baseline carbon emissions and opportunities for emissions reduction from specific actions such as switching to an electric vehicle, reducing the thermostat in winter, or switching to energy efficient equipment, taken from the US EPA (screen capture from 6/15/2022 at https://www3.epa.gov/carbon-footprint-calculator/).

Activities at Scale for Decision-Appropriate Carbon Accounting

A significant issue that is often encountered in carbon modeling is developing modeling systems that can be used directly in carbon accounting. Since carbon accounting requires reconciling carbon stocks and fluxes across space and time, they require that top-down models are connected to bottom-up estimates. *Top-down estimation methods* are generated by estimating the total net exchange of CO_2 between the biosphere and atmosphere. While attribution is difficult with these approaches, they can verify and constrain bottom-up estimates and are often combined with atmospheric transport and inversion models. *Bottom-up estimates* are generated by summing all known carbon sinks and sources from all relevant carbon-containing and carbon-emitting entities. These may include inventories, ecosystem process models or site-specific measurements from instrumented towers, remote sensing observations, or industrial activities. Bottom-up methods are often used directly in attribution, such as the emissions produced by electricity generation.

Decision support will require a significant modeling effort by the NACP community to not only reconcile these different models but increase their interoperability to allow their use in decision support. Carbon accounting methods change based on user-group interests. For example, terrestrial fluxes that are compared with atmospheric fluxes differ from life cycle analyses of terrestrial carbon stock changes (West et al., 2013). The initial measurements and estimates are the same, but the accounting and use of the information are different. By setting up a system that allows for interactive and transparent use of not only the carbon measurements, but also the modeling framework to enable immediate analysis of current conditions.

An additional aspect of decision-appropriate carbon accounting is a facility to estimate the likely impact of investments in infrastructure, the imposition of a regulation, or of a financial incentive. *Policy analysis* is a technique used in public administration to enable civil servants, activists, and others to examine and evaluate the available options to realize carbon emission reductions. Given the complexity of the climate change problem, any effective policy will require a suite of policy analysis tools, which must begin with flexible and far-reaching carbon accounting.

Communicating Uncertainty in Information and Monitoring Systems

Uncertainty quantification is a critical aspect of carbon cycle science and analysis. There are uncertainties across every aspect of carbon accounting, from the initial carbon emission observations through to the process models and downscaling of total greenhouse gases in the atmosphere. Understanding which uncertainties are the largest and most important to the overall system will help guide decisions about where to best direct resources to reduce them. This will require further analytical and comparative work, outlined in the other chapters of this plan.

Communicating the level of confidence to decision makers, as is described in section 3.5.1.2 of this chapter, will be essential. Carbon management is in its infancy, as are the policy analysis tools needed to support it. Investment and long term support of both the science and the communication across the broad set of economic, political and social/cultural sectors is essential for success. These need to focus not only on the impact of policies, but also the profoundly uncertain outcome of climate change itself. Models are not predictive of the future, particularly when technology and economic activities are involved.

Managing Risk to Governments, Institutions and Individuals

Risks from climate change are profound for society, government, institutions and individuals. Numerous studies have concluded that climate change poses risks to many environmental and economic systems. Modeling of climate change risks suggests that the coming century is likely to be characterized by challenges to food and water security (Brown et al., 2015), coastal zones (Vitousek et al., 2017), infrastructure (Dawson et al., 2018), industry (Bui and De Villiers, 2017), urban areas (World Bank Group, 2011), biodiversity (Bhuiyan et al., 2018) and human health (USGCRP, 2016). Climate change acts as a threat multiplier, exacerbating current problems of poverty, agriculture and governance (Rosenzweig et al., 2017).

These threats cut across sectors and are particularly acute for infrastructure and the ability of governments to manage them. There are strong connections between ***climate risk management***, disaster ***risk management***, and sustainable development which will either enhance or degrade our ability to reduce carbon emissions (Hausfather and Peters, 2020).

Some policies will require increased emissions in the short term, such as renewing road transportation infrastructure or increasing investment in mass transportation systems such as rail or buses. How these investments increase or reduce emissions in the long term requires research and investment. These decisions will have significant impacts on economic growth and the well-being of the US economy. For example, according to the 2018 US National Climate Assessment, the continued increase in the frequency and extent of high-tide flooding due to sea level rise threatens America's trillion-dollar coastal property market and public infrastructure, with cascading impacts to the larger economy (USGCRP, 2018). Having appropriate information on the risks, how to manage them, and whether policies are effective is the first step to appropriate management.

A decision support system for climate action is urgently needed and may benefit from support and management at the Federal level. Federal leadership of a DSS could help ensure open access and less bias for maximum benefit; although it could also impose less flexibility in the system for meeting the needs of diverse users, particularly those at the municipal, state, federal levels. NACP coordination and subsequent research could be leveraged to help accelerate decision making and implementation in the coming decade.

Key priorities for Decision Support:

1. *Establish a decision support system that elevates broader understanding of how carbon is embedded in society, and about the size of various opportunities for decarbonization linked to climate action across the wide portfolio of sectors and at a broad range of scales.*
2. *Contribute communications and outreach to elevate understanding of the nature of carbon-related climate risks attendant in decision making.*
3. *Elevate the NACP community's awareness of boundary institutions that are proving effective for bridging science to practice for a range of high-level research themes, datasets, and user communities.*
4. *Encourage and train researchers to identify potential user groups and decision makers for the outcomes of their work, and the relevant insights that may emerge from their research.*
5. *Support and engage with researchers over multiple funding cycles to create decision support tools that can ingest, present and connect to decision makers at a variety of scales.*

3.5.3 Coordination Goals:

Improved coordination across agencies, institutions and researchers would greatly improve the impact of NACP research. Coordinating among climate, land-use, global and regional economic and energy modeling would greatly improve the ability of models to interface with one another and to be more accessible for reaching diverse societal actors who seek to understand impacts across all these domains. This effort would require high-level coordination among research organizations that support modeling in different research fields, as well as by organizations seeking to use the information. In this section, we focus on how the NACP can encourage and lead efforts to ensure this coordination happens.

3.5.3.1 Coordination across modeling institutions

Modeling of the impact of climate on carbon cycling that integrates across physical, biogeochemical, and socioeconomic components of the Earth System can be quite complex, a number of quantitative models have been developed to study earth system-wide climate changes and the effect of various types of public policies on projections of future climate change. For example, one class of models, the "integrated assessment of climate change" or simply integrated assessment models (IAMs), use data from multiple sources and data modeling approaches from multiple disciplines. These models have as their objective to project alternative future climates with and without various types of climate change policies in place in order to give policymakers at all levels of government and industry an idea of the stakes involved in deciding whether or not to implement various policies (Weyant, 2017). The literature on models is spread across many disciplines, with publications appearing in a wide range of journals, including those that focus on earth sciences, biological sciences, environmental engineering, economics, sociology, technological change, and other related fields.

Coupled life cycle analysis models, which include integrated assessment, economic, biophysical and land-cover and land-use change data, can be integrated with decision support systems to improve the effectiveness of policies. Because most data collection, accounting and modeling efforts are independent of each other, using a systems approach and data assimilation, the NACP research community could integrate research areas to explore data similarities and differences and better understand sources of error across modeling frameworks. In addition, by integrating models, investments made in one sector, for example in land use change data, can be translated directly into improving carbon and economic models used in decision making. Research efforts on different methods of observing and modeling carbon sinks and emissions can be enhanced by better understanding uncertainty in existing inventory estimates and finding ways to make them more complete.

NACP can act as a coordinating institution and host meetings, research events, and sessions that bring together these diverse communities to improve modeling coordination. These efforts can focus initially on ensuring the output from one model can be used as input to another, but should eventually extend to coordinating output, decision-support tools, funding and engagement with boundary institutions.

3.5.3.2 Increasing Institutional Collaboration and Linkages

The governments' use of data – such as information collected by performance measures, environmental surveys, and findings from program evaluations and research studies – to drive decision making can help federal agencies improve program implementation, identify and correct problems, and make other management decisions. Although agencies struggle to effectively use this approach, evidence-based policy tools can help them incorporate performance information into decision making. Providing appropriate information at the right time, which all federal, state and local agencies concerned with climate change and environmental management contribute to, should greatly improve collaboration and uptake of research into decision making.

The NACP should continue to deepen collaboration with the Global Carbon Project (GCP), the Integrated Carbon Observation System (ICOS) and other global research communities to investigate North America's contributions to global emissions, the accumulation of GHGs, and the airborne fraction. By engaging with these organizations who are also supporting boundary institutions, the NACP members can enhance and accelerate their ability to engage with decision makers in the local, national and international arenas. Through international collaboration, the NACP can develop new mechanisms to communicate science findings to a variety of constituents, improving tools available to communicate results.

For example, in its 2018 work plan, ICOS has defined its target groups for provision of up-to-date information as the general public, the ICOS scientific community, and decision-makers, funders and supporters. The plan states that one of its main channels of communication is the website, with their 'Instagram and the #ICOScapes campaign' being promising and to be further invested in. Similarly, the GCP has focused one of its activities on a 'Global Carbon Budget' process, whose primary audience is the UNFCCC process and the societal actors invested in it. To this end, it has developed a conservative, incremental and regular process to issue its annual budget at the Conference of Parties (COP) every year. The NACP could expand its contribution to these campaigns, where NOAA ocean carbon data are already incorporated each year, and may consider targeting the development of specific research and models that could be instrumental in these efforts.

3.5.3.3 Improve inter-agency coordination for integrated observation and monitoring systems

The NACP can promote the goals of the Carbon Cycle Interagency Working Group (CCIWG) at the federal level. The working group coordinates carbon cycle research funded by USGCRP's member agencies. CCIWG is responsible for establishing goals, setting research priorities, and reviewing the progress of the Federal research programs that contribute to carbon cycle science. The group promotes interagency cooperation and coordination, helps to secure funding, and prepare individual and joint agency initiatives and solicitations. Because the carbon cycle is associated with a wide range of global change research needs, CCIWG works closely with other USGCRP Interagency Working Groups and engages with US and international partners.

NASA's Carbon Monitoring System (CMS) project is a good example of how the many federal agencies could work together to improve decision support and communication of the impact of a changing climate on North America and its people. The CMS project is forward-looking and designed to make significant contributions in characterizing, quantifying, understanding, and predicting the evolution of global carbon sources and sinks through improved monitoring of carbon stocks and fluxes. The approaches developed have emphasized the exploitation of NASA satellite remote sensing resources, computational capabilities, airborne science capabilities, scientific knowledge, and end-to-end system expertise in combination with effective use of commercial off-the-shelf (COTS) measurement capabilities in order to prototype key data products for Monitoring, Reporting and Verification (MRV). Significant effort is being devoted to rigorous evaluation of the carbon monitoring products being produced, as well as to the characterization and quantification of errors and uncertainties in those products.

In addition to its scientific research program, the CMS community is actively learning about and discussing a wide range of topics relevant to the program's research through practical application or as decision maker and policy context. Examples topics include greenhouse gas emission inventories, forest carbon sequestration programs (e.g., Reducing Emissions from Deforestation and forest Degradation (REDD and REDD+)), cap-and-trade systems, self-reporting programs, and their associated monitoring, reporting and verification (MRV) frameworks. Such activities depend upon data that are accurate, systematic, practical, and transparent. A sustained, observationally-driven carbon monitoring system using remote sensing data has the potential to significantly improve the relevant carbon cycle information base for the US and world. Work is needed to prototype and mature relevant measurement and analytical approaches for use in support of MRV frameworks.

The needs of management and policy domains at national, regional and municipal levels require spatial scales and timescales that are often not available. The most relevant time scales for decisions are 5-10 years, while spatial scales can reach down to activities taking place at 10s of meters. These space-time constraints do not typically match the time scales of Earth system and integrated assessment models so some level of downscaling should be involved to enhance the utility of model projections. Information which is poorly matched in time or in resolution won't be used and will leave decisions to be made without support.

NASA's Carbon Monitoring System (CMS) project is prototyping and conducting pilot studies to evaluate technological approaches and methodologies to meet this need. The NASA CMS project is a funded grant program which focuses on developing global models and policy-relevant prototype data products that incorporate remote sensing data products that can be shown to help decision makers. In contrast, NACP is a multi-disciplinary science program that incorporates a much broader set of issues, models, observations and scientists, but is primarily focused on Canada, the United States and Mexico. The NACP can explicitly address anthropogenic emissions, policy relevance, carbon cycle models and observations across a very broad set of disciplines. The two programs (CMS and NACP) have similar goals with very different mission, composition, governance, constraints and scope.

Key Priorities for Coordination:

1. *Set up systems to ensure improved coordination and interoperability among models and disciplines to generate appropriate information for decision makers.*
2. *Provide strategic and visionary guidance for institutions and actors seeking to make or inform policy and management through improved coordination and engagement.*
3. *Form linkages and clear pathways for engagement across institutions and scales for improved carbon monitoring and decision making.*

3.5.4 Conclusions and Path Forward

We may see a more complex and interconnected landscape of carbon policy and management emerge in the next 10-20 years - in particular, we're likely to see the emergence of negative emissions technology or carbon capture and sequestration at large scales, in parallel with more aggressive mitigation and adaptation efforts. This may translate to greater demands on attribution and predictive skill than currently envisioned by NACP where most of our current decision-support projects tend to be more narrowly focused on a given sector or region.

There will be a greater demand for integrating carbon decision-support frameworks with related management topics, particularly water security, food production and biodiversity. These frameworks need to be connected to improved ways of communicating scientific results via innovative and transformative partnerships and strategies to improve the understanding and impact of the research. For example, Hausfather and Peters (2020) makes a good case that it really matters how model projections are presented, and that they can influence public perceptions and policy. These developments will require developments of carbon cycle science, as well as improved methods of engaging with decision makers through boundary organizations and the co-development and application of knowledge.

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Chapter 4. Partnerships and Collaborations: Institutional, National and International

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The work of the NACP relies on a wide network of institutional and international contributions and collaborations. Strengthening and widening these connections is a key priority for the program's future for several reasons: ensuring relevance and contributing to global understanding; breaking down agency, institutional, and national barriers that prevent scientific advancement; and enhancing NACP resilience to potential variations in funding priorities and availability.

NACP science contributes to global understanding of the carbon cycle by engaging scientific networks and decision-makers, testing and developing scientific methods, bolstering observing systems, uncovering fundamental process-level understanding, and communicating findings. Expansion of institutional and international collaborations will facilitate achievement of the program's aims, and will allow for greater coordination of North American contributions to carbon cycle science and decision-making across a range of scales (local, regional, national, continental, to global).

Research Partnerships Among Agencies and Universities

The NACP's origins are rooted in coordination and funding initiatives among several US Federal Agencies (e.g. NASA, NOAA, DOE, USDA, USGS, and NSF). Since initiation, these agencies have funded research scientists at diverse institutions, including universities, research institutes, and governments. The establishment of NACP enabled investment and collaboration at scales beyond an individual investigator or even agency mission. For example, the Mid-Continent Intensive (MCI) synthesis in the 2000s served as a test-bed for methodologies used to validate and compare regional carbon flux estimates derived from "top-down" atmospheric budgets and "bottom-up" ecosystem inventories, facilitating further evaluation and improvement of both approaches. NASA, NOAA, DOE, USDA, and NSF funded 45 projects resulting in 200+ publications. This research was foundational, along with other NACP synthesis activities on model intercomparison, coastal carbon, disturbances, and site-level analyses, in providing the underlying scientific understanding for the First (2007) and Second (2018) State of the Carbon Cycle Reports.

Despite the successes of US Federal competitive research funding for carbon cycle science, there are ongoing challenges for establishing and maintaining research projects, partnerships and cross-federal collaborations. Changes in presidential administration, differing agency missions and mandates, and administrative constraints on funding duration and mechanisms (e.g., limitations on type of institution or cross-agency transfer of funds) all potentially hinder activities that require intensive or long-term investment and coordination. Meanwhile, rapid evolution of societal information needs from carbon observing and modeling communities underscores the importance of expanding partnerships to new sectors, including state and tribal governments, industry, and other end-users of carbon cycle data and information products.

Science Communities of Practice

NACP now functions as a *community of practice* (Brown et al., 2016). A community of practice is defined as "a group of people who share a common set of problems, or a passion about a topic, and who deepen their knowledge and expertise in this area by interacting on an ongoing basis." Individuals and institutions within the NACP network have become more interconnected over time through continued participation in shared practices, with NACP serving as a platform for researchers representing different institutions and with complementary expertise to engage in cross-organizational collaboration. The NACP community of practice continues to grow by extending to a wider range of relevant disciplinary topics, most notably incorporating more human dimensions into its research profile.

Continued investments in community building and shared activities are needed to sustain a vibrant NACP science community of practice and to reduce interoperability barriers that hamper cross-institutional, transdisciplinary, and potentially transnational collaborations. The roles of the NACP Coordinator, the NACP Science Leadership Group, and the commitment to convening NACP Open Science Meetings all help to maintain, nurture and expand the NACP community. NACP involvement in national and international assessments such as the State of the Carbon Cycle Reports and the National Climate Assessments, are efforts of a collaborative multi-institutional community.

Given the scientific needs from the community, the NACP, with the assistance of the US Carbon Cycle Science Program, will increase efforts to enhance connections between NACP and communities with similar or overlapping research interests. Connections between NACP and other US-based efforts include approaches with different US federally sponsored programs (e.g., US Ocean Biology and Biogeochemistry Program (OCB)), research networks, and non-academic and private sector organizations (see below). Furthermore, NACP recognizes the need to promote and enhance relationships with international efforts. Bridging connections to adjacent programs and efforts will add value by enhancing programmatic coordination, realizing strategic synergies, exchanging ideas, elevating impact, and facilitating new initiatives that cut across scales and boundaries.

There are justice, diversity, equity, inclusion, and accessibility benefits in enhancing partnerships across networks, institutions, and international borders. By lowering barriers to interoperability, investment in these relationships would expand the accessibility, useability, exchange, and visibility of the science, tools and products among the broader NACP community. They would also potentially create new career pathways for developing innovative products to advance common goals and meet practitioner needs.

There are several key priorities for enhancing the NACP community through institutional, national and international partnerships:

1. **Non-Academic Institutions and Carbon Cycle Practitioners**
   There are several private sector companies, non-governmental organizations, and other practitioner groups that focus on carbon management (e.g., National Indian Carbon Coalition (NICC), Project Drawdown, Enviva, Danone North America), and there is large potential for NACP to offer its scientific expertise while creating opportunities for co-production of knowledge that will be usable and actionable. For instance, the NICC is one organization explicitly dedicated to engaging Native American communities in carbon management. 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. 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 (McCarthy et al. 2018). While the pace of the private sector's adoption of carbon reduction and removal strategies has accelerated in the past, the rate of integration of existing and rapidly developing new science into such strategies has lagged. ***In the next few years, the NACP should expand collaborative activities with non-academic organizations, NGOs and the private sector through targeted use-inspired science and joint interaction platforms, iterative discussions and joint product development opportunities to help meet these needs and bring the best available information to address the needs of this sector.***

2. **National Institutional Priorities**
   Research Networks: Collaborative, multi-institutional research networks provide essential platforms for sustained long-term observations, high-impact cross-site comparative analyses and synthesis, methodological innovations, and manipulative experiments to develop new knowledge. Beyond the well-known federal agency programs, such as the NOAA Global Greenhouse Gas Reference Network, the USGS water quality and stream gauge network, and the USDA forest inventory and analysis program, multi-institutional research networks involve diverse partnerships and investments. Many of these collaborative communities are spawned by large federal investments, but then grow into long-term, sustained networks. Examples include LTER, LTAR, AmeriFlux, ABoVE, US National Phenology Network, and MsTMIP among many others. NACP already has connections to several of these research networks, though some are more developed than others. ***NACP will maintain and expand connections with relevant research networks, including exploring joint activities and other collaborative efforts.***

3. **Continental Priorities**

   Collaborations across Canada, the US, and Mexico: The NACP is a US-based effort established by US Federal agencies participating in the US Carbon Cycle Science Program and does not represent the interests of other countries. The NACP community has been largely composed of individuals from US institutions but research has not been limited to carbon cycling within US borders. Therefore, the NACP community recognizes the importance of cross-boundary collaborations and engagement with respective federal and Indigenous agencies and institutions to fully understand the carbon cycle across North America. A recent example has been the participation of multiple agencies and institutions from Canada, US, and Mexico to contribute to the Second State of the Carbon Cycle Report (USGCRP, 2018).

   One initial tri-national effort by the mid-2000s was the Joint North American Carbon Program (JNACP). This effort became known as CarboNA, which is a joint government-level initiative among Canada, US and Mexico. The goal of CarboNA is "to establish greater cohesion across North America in the fields of carbon pool and greenhouse gas flux dynamics and for carbon related mitigation strategies through the identification of continental-scale priority issues and promotion of collaborative research in areas of common interest and complementary expertise". CarboNA originally had a Government Coordination Working Group and a Science Steering Committee, but political, funding, and logistical difficulties and changes have meant that this effort is not currently active. During a CarboNA breakout session in the 2017 NACP Principal Investigators Meeting, participants concluded on the interest and need of investing efforts and resources towards CarboNA. The general message was that CarboNA is a useful tri-national initiative that enhances communication and collaboration about carbon cycle science across the three countries. Therefore, there is an opportunity for NACP to strengthen connections with Canadian and Mexican colleagues involved in carbon cycle research. ***The NACP Coordinator and SLG should look for ways to expand engagement with those at Canadian, Mexican, and Indigenous institutions, finding meaningful ways to build a continental community that supports the needs and interests of carbon cycle science researchers throughout North America. Revisiting the tri-national agreement for CarboNA and restructuring this committee in light of current goals and needs should be a priority to formalize continental collaborations. The NACP should consider outreach and engagement activities with Indigenous institutions to develop collaborations and partnerships as well.***

4. **Global Partnerships**

   US agencies contribute to global efforts through programs such as the Committee on Earth Observation Satellites, the Group on Earth Observations, the Global Ocean Observing System, and the World Meteorological Organization's Global Atmosphere

Watch. Continued and expanded cooperation with international partners is needed. These international collaborations improve efforts for validation and characterization of remote sensing datasets needed to ensure consistency of products across platforms and over time. International cooperation is also needed on in situ surface, aircraft, and oceanographic measurement networks. These international efforts complement and anchor multiple data streams and define best practices and common standards and data formats. With support and guidance from the NACP Office, the US Carbon Cycle Science Program Office and participating agencies, the NACP community would benefit from expanding and further fostering its liaison, coordination and collaboration activities with key regional and international groups, including (but not limited to) the Global Research Projects of Future Earth (e.g., the Global Carbon Project, GCP), the Intergovernmental Panel on Climate Change (IPCC), the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), International Long Term Ecological Network (ILTER), the World Climate Research Program (WCRP), the Integrated Carbon Observing System (ICOS), the Integrated Global Greenhouse Gas Information System (IG3IS), FLUXNET, Coastal Carbon Research Coordination Network (CCRCN), Coastal Rainforest Margins Research Network, and the Permafrost Carbon Network. ***NACP should maintain and expand connections with relevant global partners, including exploring joint activities and other collaborative efforts.***

Conclusion

The NACP has identified priorities for each program element as described in Chapter 3. These are ambitious and require collaboration and coordination among researchers, practitioners, current/potential partners and other actors in business, government and civil society. This Chapter identified actions to strengthen partnerships and collaborations that are essential to ensuring the success of other program elements. These national and international collaborations will support and grow the NACP community of practice, advance equity and justice in our community and the communities that our research serves across North America, and ensure the regional-to-global relevance of our work.

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Chapter 5. Data and Information Management

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5.1 Introduction

The goal of data and information management for NACP is to ensure data products required and produced by various elements of NACP are readily available when needed and in forms that are convenient to use by different types of users. As outlined in the 2005 NACP Science Implementation Strategy (Denning et al., 2005), key functions of data and information management include acquisition, distribution, and sharing of key data; centralized access to NACP data; standards for data and documentation; quality assurance reviews; tools to facilitate data acquisition, visualization, and analysis; data processing; and preparation of value-added data products. Effective data and information management is fundamental to the success of every element of NACP, including observations, assessment and integration, modeling, communication, coordination and decision support. These key functions still remain central to the program, their scope and extent require expansion and deepening, as new data needs and challenges emerge.

NACP established its Data Policy in 2007 to ensure that participants have full, open, and timely access to NACP data. This Data Policy pertains to the life-cycle of data during NACP – from data collection, through quality checking and analysis, to distribution to NACP participants, and to depositing finalized products in a long-term archive.

The Modeling and Synthesis Thematic Data Center (MAST-DC), funded by NASA's Terrestrial Ecology (TE) Program, was a core data management component of NACP. MAST-DC was designed to support NACP by providing data products and data management services needed for modeling and synthesis activities. Based on data needs identified through the NACP data management workshop held in 2005, MAST-DC coordinated data management activities with NACP modelers and synthesis groups, prepared and distributed model input data, provided data management support for model outputs, provided tools for accessing, subsetting and visualization, provided data packages to evaluate model output, and supported synthesis activities, including data support for workshops. MAST-DC was a key to the success of NACP modeling and synthesis activities, including the Site Synthesis, the Regional Synthesis, Mid-Continent Intensive Interim Synthesis (MCI), and Multi-scale Synthesis and Terrestrial Model Intercomparison Project (MsTMIP). The significance of MAST-DC went beyond the course of the project in that it provided data management guidelines that facilitated the data practices across the NACP community (Cook et al., 2018; https://daac.ornl.gov/datamanagement/).

Through more than a decade of effort sponsored by multiple agencies, NACP has collected and produced a huge amount of data products, including more than 450 that have been archived and are publicly available, as well as about 300 more under development (as of

July 2022) in the NACP Database. This diverse collection of data products includes field measurements, in-situ observations, inventory, airborne and spaceborne remote sensing, synthesis results, and modeling products. These data are managed at various long-term data facilities and repositories across different agencies, including the NASA Earth Observing System Data and Information System (EOSDIS), DOE's Environmental Systems Science Data Infrastructure for a Virtual Ecosystem (ESS-DIVE), USFS Forest Inventory and Analysis (FIA), USDA National Agricultural Statistics Service (NASS), and NSF NEON and LTER Networks, Biological & Chemical Oceanography Data Management Office (BCO-DMO), and NOAA National Centers for Environmental Information (NCEI). The Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC), a member of NASA EOSDIS, serves as a major long-term data archive for data products from NASA's Terrestrial Ecology program and Carbon Cycle & Ecosystems focus area, including data from projects such as ACT-America, ABoVE, and CMS. ESS-DIVE serves as the major data repository for DOE's Environmental System Science and the new home for data products of the long-standing CDIAC. NOAA NCEI archives sustained observational data sets from coastal and open ocean carbon cycle observations.

Those data resources provide a foundation to tackle NACP science questions and have potential for reliable state-of-the-science decision support services to policymakers and diverse actors in society. However, the very large volume of data and the distribution of this data across multiple data repositories and organizations pose challenges on NACP research and development activities and also the use of NACP data and results in downstream applications.

5.2 Data Needs and Challenges

Research and development priorities identified in the major NACP elements pose emerging needs and challenges on data and information management. This NACP Science Implementation Plan called out the research needs for 1) sustained and expanded observations, 2) a comprehensive Carbon Monitoring System that integrates observations and analysis systems across scales, sectors, and agencies to transform current capabilities into a coherent and coordinated system that reports the current state of the carbon cycle and provides timely detection and attribution of its patterns and trends, and 3) a Carbon Decision Support System to answer pressing new questions and needs arising from diverse societal actors leveraging the data and findings from NACP research activities. Through a parallel comparison with numerical weather prediction systems, Ciais et al. (2014) described the current hurdles and the importance of improved data management, infrastructure, and services for a future policy-relevant operational carbon observing system. Similarly, for NACP, a pressingly needed backbone to support these research priorities is a data and information management system that promotes FAIR (Findable, Accessible, Interoperable, and Reusable) data (Wilkinson et al., 2016); appreciates and addresses CARE (Collective Benefit, Authority to Control, Responsibility, and Ethics) principles for Indigenous Data Governance (Carroll et al., 2020; Carroll et al., 2021); seamlessly integrates data across scales, domains, systems, agencies; and enables easy and timely data sharing, discovery, visualization, access, and analysis. The key data needs and data system elements are described below.

5.2.1 Permanent data archival

Scientists need sustained options for permanent data archival. Most agencies now require a data management plan addressing the permanent, public, archival of data collected on all funded grants. Some agencies also have dedicated repositories for long-term data preservation. In addition, nearly all journals require electronic release of data simultaneously with paper publication. We applaud such policies to promote the reuse of data and the reproducibility of results. However, while agencies and journals require archival, many do not offer such services. and even if they do, archival of data from continuous efforts co-funded by multiple agencies can still cause complexity. For example, a data center funded by one agency generally cannot archive data collected under a grant from another agency without special arrangements, even if the data clearly fall under the data center's mission and the data center has very related data from other aspects of that same investigator's work. These issues force investigators to 'shop around' for a data center to accept their data, cause similar data to be archived with differing practices and levels of curation, and make it more difficult for data users to find and use related NACP data. A coordinated strategy and effort within and across agencies participating in the NACP are needed to address this community need.

5.2.2 Data interoperability

Data interoperability addresses "the ability of systems and services that create, exchange and consume data to have clear, shared expectations for the contents, context and meaning of that data" (https://datainteroperability.org/). With the continuously increasing diversity and amount of data used for and produced by NACP, making data interoperable on both structural and semantic aspects is crucial for effective data integration and use. Common standards for data format, metadata, and vocabulary are needed for data interoperability. Some standards exist, such as the Climate and Forecast (CF) and the Assistance for Land-surface Modeling Activities (ALMA) conventions, but these focus on modeling and lack terminology for many disciplines. Many groups are working on standards, but if every data center has a different standard, the time required to organize Big Data remains unchanged. We should coordinate the enhancement, development, and adoption of standards across data centers. The ocean carbon community has engaged in a number of collaborative international data assembly and secondary quality control projects that facilitate data contributions by investigators across numerous agencies and countries and ultimately allow for greater data interoperability and accessibility for end users (e.g., Bakker et al. 2016; Olsen et al. 2020). The Surface Ocean CO_2 Atlas and Global Ocean Data Analysis Project could provide a useful model for future NACP data interoperability efforts.

5.2.3 Data discovery and access

Different agencies have invested a fair amount of effort in improving the discovery of and access to their data. For example, since its establishment in early 1990s, NASA's EOSDIS has been long dedicated to managing and enabling discovery and access to diverse NASA Earth science data (Behnke et al., 2019). DOE's ESS-DIVE was launched in 2017 to store and publicly distribute data from observational, experimental, and modeling research funded by the DOE's Office of Science under its Subsurface Biogeochemical Research (SBR) and Terrestrial Ecosystem Science (TES) programs within the ESS activity. But NACP researchers do not have a central gateway to share data and results across teams and agencies and for the general public to find and access NACP results and findings of interest. The exponentially growing volume of data and the advancing computing technologies offer new opportunities for data-intensive approaches, including advanced data assimilation, machine learning (ML), and cloud-based analysis. But at the same time, it requires that data are not only easily accessible, but also accessible in interoperable, ready-to-use forms, for example, being analysis-ready, ML-ready, and cloud-ready. Agencies like USGS, NASA, and NOAA have started new initiatives to satisfy the data and information needs of modern research, for example the Committee on Earth Observation Satellites (CEOS) Analysis Ready Data for Land (CARD4L) and NASA EOSDIS's cloud migration efforts. Cross-agency coordination is needed to leverage those existing data and information initiatives to address the data discovery and access needs of NACP.

5.2.4 Data tools for non-expert users

NACP data products are valuable for the broad user community, including non-expert users and decision makers, not just NACP-funded researchers. Successful understanding and use of those data by local, state, and national decision makers and the general public is important to maximize the value of NACP research findings and increase the recognition of the importance of NACP activities. For example, data products produced by NASA's CMS projects provide emissions, biomass, carbon flux products (Gurney et al., 2020) across scales and sectors in support of local- and regional-scale carbon MRV. But due to the complexity of these data products, they are not readily understandable and usable by non-expert users, even if the data are easily findable and accessible. There is a need for easy-to-use Web-based data tools, particularly ones that interoperate with commonly used geospatial information system (GIS) tools, to summarize complex data products, visualize information in intuitive ways, and communicate NACP findings to decision makers and the general public.

5.2.5 Data and information quality

Data quality information, such as associated uncertainty and provenance, is important to determine the fitness-to-use of individual datasets and for the traceability and reproducibility of scientific findings. It is an essential part of the ecosystem that supports open and actionable science. With the anticipated developmental progression to expand the

NACP to advance predictive capability and to support decision makers, there is an increasing need for standards, guidelines, and best practices to improve the representation, interoperability, accessibility, and usability of data quality information. Earth Science Information Partners (ESIP), a community formed with 120 partner organizations including many agencies participating in the NACP, established the Information Quality Cluster (IQC) to develop and publish a baseline of standards and best practices for data quality for adoption by inter-agency and international data providers. ESIP IQC defined the four dimensions of data quality: scientific, product, stewardship and service (Ramapriyan et al., 2017), devoted efforts to provide consistent understanding of the various perspectives of Earth science data uncertainty (Moroni et al., 2019), and initiated the action for global access to and harmonization of quality information of individual Earth science datasets (Peng et al., 2021; Peng et al., 2022). Through the coordination of USGCRP, the National Climate Assessment (NCA) established an information system to capture provenance that provided scientific support for the findings of the assessment (Tilmes et al., 2013). Such capability is of importance to the NACP findings as well. Existing communities such as the ESIP IQC can provide platforms for cross-agency discussion and collaboration to address the data quality needs to improve the efficiency, trustworth, and value of NACP research and products.

5.2.6 Data needs for Artificial Intelligence applications

Artificial intelligence (AI), particularly ML in which computers learn from data, has been applied in many domains of Earth science (Maskey et al., 2020; Irrgang et al., 2021) and its applications have been rapidly growing, thanks to the enormous data being collected and advancement of computing technologies. Even though data needs of ML applications cover the same aspects (e.g., discovery, interoperability, accessibility, and data quality) as for other applications, they pose further and even unique data challenges (Maskey et al., 2020), for example, a lack of publicly available benchmark training data sets with reliable and structured labels across science disciplines, including carbon cycle science; more rigorous requirements on data interoperability to allow data being reused by ML models; additional data quality requirements to minimize bias of ML models due to under-representative samples or false signals in training data. Metadata and documentation about models/data and open sharing of such information is especially important to ensure ML application results can be traced and reproduced and to prevent data and models from being misused. For example, Google initiated the “Model Cards” effort to help organize the essential facts of ML models in a structured way (Mitchell et al., 2019). The NACP, the broader Earth science, and ML communities would benefit from further collaborations to address these challenges and develop innovative solutions to geoscience problems.

5.2.7 Data management practices and dedicated support

The NACP community still needs improved data management practices and personnel with relevant skills to build a healthier open data ecosystem to promote research and applications. Furthermore, there is an increasing need to develop guidelines and best practices to educate the future carbon cycle researchers to be well prepared for innovative, interdisciplinary research bridging Earth science and AI. Funding agencies need to ensure that research projects have an appropriate level of resources dedicated to data management. Access to sufficient storage to facilitate extended analysis and information product development from hindcasts, forecasts, and projections on various timescales is still uneven across Federal agencies. Resources committed to long-term archival, development of data tools and services, and integration across data systems are needed to maximize the research and societal value of NACP data products. Improved data management practices and skilled personnel are important to ensure smooth interaction between research teams and data systems and to form a seamless data lifecycle to promote science and applications.

5.3 Data and Information Management Priorities

To address the emerging data needs and challenges to advance the observation, synthesis, modeling, and decision support activities outlined in this NACP Science Implementation Plan, an effort dedicated in coordinating the next generation data management and synthesis activities across NACP would be critical. Instead of setting up a central long-term data repository for NACP, this effort will coordinate among agencies to support data management across NACP by providing dedicated personnel and establishing channels for cross-agency NACP data experts to tackle data challenges and identify concrete solutions in a collaborative manner. This work includes reviewing the NACP Data Policy and providing options for high-quality, permanent, data publishing regardless of funding source. This effort will also lead the development of necessary infrastructure, based on emerging information technologies (e.g., cloud computing), required for integration across data systems by leveraging community standards (such as science on Schema.org) and lessons learned from prior NACP management projects (e.g., MAST-DC) and related Earth science efforts (e.g., DataONE; Michener et al., 2012). This work is crucial to enabling effective data discovery and seamless data access mechanisms across agencies. It will also serve as the interface to collaborate with existing data and information communities beyond NACP, such as Open Geospatial Consortium (OGC) and ESIP, to advance the development of standards, guidelines, and practices to promote data quality, interoperability, and sharing needed by NACP.

With the rapid growth of NACP data and research, needs and challenges for data are also rapidly evolving. It is important to have a dedicated effort to consistently coordinate activities, such as data management workshops, among domain scientists, data researchers, and other users across NACP to ensure new data needs and challenges are captured in a timely manner, adjust and improve the strategies and approaches to address the emerging needs, and also provide necessary and timely training on data management practices to the NACP community.

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