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2021 NACP Science Implementation Plan

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Chapter 1. Introduction

Lead Author: Christopher A. Williams; **Contributing Authors**: Arlyn Andrews, Molly Brown, Kenneth J. Davis, Forrest M. Hoffman, Benjamin Poulter, Eric T. Sundquist

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 Earth's biosphere. 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 responds to continued and growing urgency to understand the dynamics and drivers of the coupled carbon-climate system, and its interactions with the health and sustainability of ecosystems, natural resources, and the provision of goods and services.

1.2 The NACP

With a focus on sources and sinks of carbon for North America and its coastal waters, 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.

1.3 Program Foundation and Developmental History

The North American Carbon Program (NACP) is a principal activity of the US Carbon Cycle Science Program (USCCSP), a Federal interagency partnership that operates under the aegis of the U.S. Global Change Research Program (USGCRP). Born out of the 1999 US Carbon Cycle

Science Plan (Sarmiento and Wofsy 1999) (Figure 1), 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 U.S. 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 U.S. 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.

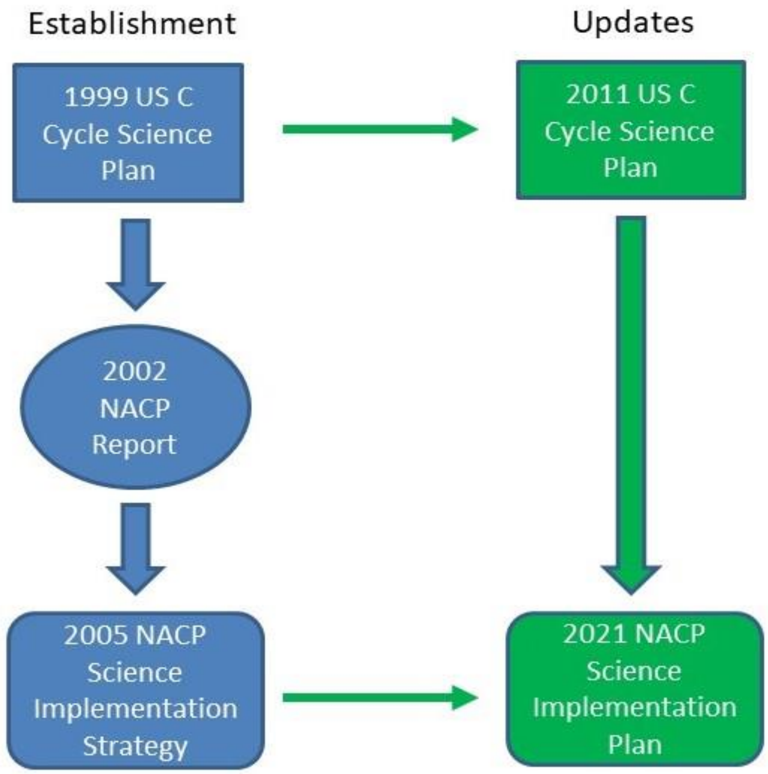

Figure 1. Establishment of, and updates to, the North American Carbon Program (NACP), from its origins in the US Carbon Cycle

Science Plan to its design laid out in science implementation documents.

1.4. The 2021 NACP Science Implementation Plan

This 2021 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 (Chapter 2), 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). An Executive Summary underscores the most important aspects of the implementation plan.

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 at NASA Goddard Space Flight Center. 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, NGOs, and 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. However several new dimensions have emerged, including increased 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 2021 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.

2021 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 Since NACP’s Founding

Great 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 understanding 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, 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 even with spaceborne, remote detection of greenhouse gas concentrations.

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, including through collaboration with 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/or greater detail. This includes critical contributions from programs such as the USDA Forest Service Forest Inventory and Analysis, the USDA National Agricultural Statistics Service, the USDA Natural Resources Conservation Service Rapid Carbon Assessment, and the USGS Groundwater, Streamflow and Water Quality monitoring programs.

NASA established a prototype Carbon Monitoring System (CMS) leveraging existing observation programs from across NASA and other agencies, and some individual projects include additional targeted measurements 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 U.S. 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 stakeholders 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.

Databases documenting fossil fuel and cement emissions, such as the early Carbon Dioxide Information and Analysis Center (CDIAC), have seen continued improvements in spatial resolution and with the chemistry of fuels, for example by 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.

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.

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.

Large-scale research intensives have been launched (e.g. Mid-Continent Intensive, ABoVE, 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 launched. As just one example from an LTER 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 and thawing of permafrost.

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 predictions.

The NACP has engaged in extensive reporting, communication and outreach activities. These include major contributions to the USGCRP Sustained Assessment Report on the State of the Carbon Cycle Report (SOCCR), with additional contributions to the National Climate Assessment (NCA). The NACP has contributed to the Global Carbon Project, including its Regional Carbon Cycle Assessments and Processes (RECCAP) initiative. 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 (https://nacarbon.org/cgi-bin/web/investigations/inv_profiles.pl#post2013), 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. The program's communications, outreach, and decision support dimensions are under-developed, undermining the program's ability to inform the public and address decision maker needs.

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 over the past decade, including FLUXNET - Canada, the USGS hydrological monitoring network, and NOAA's atmosphere and ocean sampling networks. 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 USFS, NOAA, and USGS offices has jeopardized the critical contributions these institutions make to carbon cycle research.

References

Denning, A.S. et al. 2005. Science implementation strategy for the North American Carbon Program. Report of the NACP Implementation Strategy Group of the U.S. Carbon Cycle Interagency Working Group. Washington, DC: U.S. Carbon Cycle Science Program.

Michalak A., Jackson R., Marland G. and Sabine C, co-chairs. 2011. A U.S. Carbon Cycle Science Plan : A Report of the Carbon Cycle Science Steering Group and Subcommittee

Sarmiento, J.L. and S.C. Wofsy. 1999. A U.S. Carbon Cycle Science Plan. A Report of the Carbon and Climate Working Group for the U.S. Global Change Research Program. Washington, DC: U.S. Global Change Research Program.

Wofsy, S.C. and R.C. Harris. 2002. The North American Carbon Program (NACP). Report of the NACP Committee of the U.S. Carbon Cycle Science Steering Group. Washington, DC: U.S. Global Change Research Program.

Chapter 2. Program Elements and Leading Initiatives for the Future

Lead Author: Christopher A. Williams; **Contributing Authors**: Arlyn Andrews, Molly Brown, Kenneth J. Davis, Forrest M. Hoffman, Benjamin Poulter, Eric T. Sundquist

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 2021 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 2021 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.

Assessment and Integration (Chapter 3.2) seeks to produce key scientific data products and to develop analytical methods needed for synthesis and integration 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, Outreach, 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 and the Executive Summary emphasize the highest-level needs and initiatives for the program's future.

2.2 Leading Initiatives for the Future of NACP

The following themes and initiatives are of highest priority for the program's future.

Sustained, long-term observations and research networks will continue to serve 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.

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. 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 internal consistency across sectors and reporting units, and including checks across measurement systems and scales.

A Carbon Decision Support System is needed to answer pressing new questions and needs arising from diverse stakeholders who are asking NACP to play a lead role. Its mission will be 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 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 actions can have meaningful impacts at scale.
- Mapping the carbon economy, including quantification and visualization of virtual fluxes embedded in production and consumption activities across sectors.

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, and changes in atmospheric composition. 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 novel 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.

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.

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****** SOFT RELEASE FOR COMMENTS BY NACP COMMUNITY******

Chapter 3.1: Sustained and Expanded Observations

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IMPORTANT NOTE: THIS DRAFT HAS NOT YET BEEN REVIEWED BY THE ENTIRE WRITING TEAM. INPUT IS WELCOME AT THIS STAGE AND SUBSTANTIVE CONTRIBUTIONS WILL BE ACKNOWLEDGED ACCORDINGLY. A MORE POLISHED AND COMPLETE DRAFT, INCLUDING APPENDICES, IS ANTICIPATED BY EARLY APRIL 2021.

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 SOCCR-2 and in this document.

In the US, responsibility for carbon observations does not reside within a single agency. EPA leads the effort to collect and compile data from a number of other departments and agencies and produce an annual inventory of 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 Science Program. 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.

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 Decadal Survey for Earth Science and Applications from Space. 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 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. Careful monitoring and process studies to advance understanding of the *global* carbon cycle are thus urgently needed to support climate policy and mitigation and adaptation efforts by the US and other nations. Sustained and rigorously calibrated measurements are needed to support implementation of UNFCCC efforts such as Reducing Emissions from Deforestation and Forest degradation (REDD+) and the Global Stocktakes in 2023 and 2028 to evaluate Nationally Determined Contributions (NDCs) under the Paris Agreement. 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 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^{3}IS) aiming to expand the observational capacity for greenhouse gases, extend it to the regional and urban domains, and develop the information systems and modelling frameworks to provide information about GHG emissions to society. IG^{3}IS 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[1]. GCOS recommends targeting efforts to sample data-poor regions and regions sensitive to climate, and calls for carefully planned conversion of research 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.

Current and Planned Observations

Sustained Observations

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[1] Updated ECV measurement requirements are currently under review until 2022.

Detection of climate change signals requires measurement records of sufficient duration to characterize other sources of seasonal and interannual variability such as ENSO. Carbon observing networks should be designed to track responses to interannual variability in climate as well as human decision making/management through time. 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, and recent best estimates of the carbon budget were synthesized in the SOCCR-2. 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, 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 (SOCCR-2 page 349, Section 8.6), 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 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.

Expanded datasets are needed for ongoing assessment of mitigation strategies and/or management of climate impacts. For example, 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. Forest carbon offset programs must have reliable verification mechanisms. Many US cities and states have enacted climate adaptation plans that include aggressive greenhouse gas reductions. Reliable datasets are needed to ensure that mitigation efforts are on track to meet ambitious targets.

Current and planned observational capabilities, major findings and decision support services, gaps and limitations, and anticipated measurements and emerging technologies are described in Appendix A1 (forthcoming in April 2021) as follows:

A1.1 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. Major US observing systems include NOAA's Global Greenhouse Gas Reference Network (GGGRN), NSF's National Ecological Observatory Network (NEON), the NASA Orbiting Carbon Observatory - 2/3, and the Total Column Carbon Observing Network.[2] NASA's planned GeoCarb geostationary mission, planned for launch in 202X) will alternately view the continental US and the Amazon basin and will provide several soundings per day with nearly complete spatial coverage for each region.

Measurement requirements for estimating regional fluxes are extremely challenging, especially for CO_2, since signatures of surface fluxes are small and are superimposed on a large and highly variable background. Vertical profile measurements extending from the surface through the planetary boundary layer and well into the free troposphere 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. Total column measurements from satellites can potentially provide comprehensive coverage during daylight cloud-free conditions[3], but they are relatively insensitive to regional surface fluxes and are subject to systematic biases in retrievals that can overwhelm

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[2] Urban and point-source monitoring efforts are included in Appendix A1.2 Anthropogenic Emissions.

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

surface flux signatures. The US lacks a long-term strategy for coordinated in situ and satellite measurements of atmospheric CO_2 and CH_4.

A1.2 Anthropogenic Emissions

In the US, national total emissions and removals are reported by the EPA in its annual Greenhouse Gas 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). 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. Emissions of greenhouse gases are often directly 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 lack the spatial and temporal resolution needed for data assimilation and inverse modeling studies. Some 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) and CH_4 (Maasakkers et al., 2016) 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, and state agencies in California and New York have explored the potential of using atmospheric monitoring to estimate state-level emissions. Measurements of radiocarbon in atmospheric CO_2 provide independent estimates of fossil fuel emissions for evaluating inventories and could be expanded to track regional and national trends. New and upcoming satellite sensors have been optimized to map plumes from large point sources and urban areas are expected to greatly 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, have taken a leading role in developing new approaches for tracking anthropogenic emissions from space.

A1.3 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 U.S. 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 U.S. 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 to enable tracking of changes in 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. 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 to provide additional detailed spaceborne measurements of vegetation traits, and candidate measurement approaches include hyperspectral imaging. 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 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 2022. 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 to provide additional detailed spaceborne measurements of vegetation traits, and candidate measurement approaches include hyperspectral imaging.

A1.4 Terrestrial Ecosystem Fluxes and Drivers

Terrestrial ecosystem fluxes can be derived from changes in stocks as indicated by inventories and other data products or by direct observations. The USDA Forest Service is responsible for reporting nationally and internationally on greenhouse gas emissions and removals from forest land, woodlands, urban trees in settlements, and harvested wood products as part of the Environmental Protection Agency Greenhouse Gas Inventory which is prepared each year as part of the US commitment to the United Nations Framework Convention on Climate Change. 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. Major US long-term observing systems include AmeriFlux (DOE), and the National Ecological Observatory Network (NSF), Critical Zone Observatories (NSF), the Long Term Ecological Research sites (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 soil 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.

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. An NDVI time series has also been developed from Landsat. 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 datasets 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 the Tropical Rainfall Measuring Mission (TRMM) Visible and Infrared Scanner (VIRS) 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.

A1.5 Inland Waters and Terrestrial Wetlands

PLACEHOLDER FOR OVERVIEW PARAGRAPH

A1.6 Coastal Margins

PLACEHOLDER FOR OVERVIEW PARAGRAPH

PLACEHOLDER FOR SHORT SECTION ABOUT ANCILLARY MEASUREMENTS

- Meteorological measurements to improve atmospheric transport simulations and reduce uncertainty of top-down estimates
- Soil moisture
- Geologic information to measure subsurface hydrology
- etc

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 are often leveraged or designed 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.

A series of coordinated multidisciplinary intensive experiments were 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 an overview of intensive experiments with strong links to NACP. More detailed information is provided in Appendix A2 (forthcoming in April 2021).

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. SOCCR-2 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.

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. US cities with extensive GHG measurement programs include 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 measured plumes downwind of urban centers along the US East Coast to estimate emissions of CO2, CH4, and CO during Spring 2018 and 2020, respectively. Notably, they found evidence of large fugitive CH4 emissions and estimated total emissions more than double EPA inventory estimates. ECO COVID-19 revisited the region to assess the impact of coronavirus responses on air quality and greenhouse gas emissions.

Intensive atmospheric observations have played a major role in quantifying emissions from oil and gas production and from coal mining. Flights downwind of major production regions have shown widely varying and frequently larger than reported emissions (e.g. Peischl et al., 2018 Smith et al., 2015; Barkley et al., 2019; Petron et al., 2020). 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). 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.

PLACEHOLDER FOR TERRESTRIAL/COASTAL INTENSIVES.

- Intensive data collection sponsored by NASA CMS (e.g. lidar for regional/state level biomass)
- Coastal ocean intensives: EXPORTS
- Other?

Manipulative Experiments

PLACEHOLDER FOR FACE EXPERIMENTS.
PLACEHOLDER FOR NGEE-SPRUCE.
PLACEHOLDER FOR SOIL EXPERIMENTS.
OTHER?

Chapter 3.1 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.
    - Greatly expanded vertical profile measurements of atmospheric CO_2, CH_4, and CO are urgently needed to reduce uncertainties in top-down flux estimates and to correct systematic errors in current and future satellite data products that are comparable to or even larger than the signals of surface fluxes. Commercial aircraft are a promising platform for increasing the frequency of profiles by an order of magnitude.
    - 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 to enable tracking of changes in SOC resulting from land management practices or climate change.
    - 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.
    - PLACEHOLDER FOR OTHER KINDS OF OBSERVATIONS (ground-truth for lidar/radar estimates of biomass, ocean biogeochemical properties, etc.)

- **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).
    - Rigorous Observing System Simulation Experiments 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.** Data products that accurately represent diurnal and day-to-day variability are needed to enable rigorous evaluation of process models and inventories using atmospheric measurements.
    - 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, 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.
    - 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, and well-characterized uncertainties and error covariances are needed for atmospheric data assimilation systems. Placeholder for examples of promising products that could be transitioned from R&D to routine operations.

- **New coordinated intensive measurement activities to address key uncertainties identified in SOCCR-2.** A solicitation for whitepapers proposing new NACP intensive measurement campaigns is suggested.

- ○ 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.
- ○ PLACEHOLDER FOR ADDITIONAL INTENSIVE CAMPAIGN SUGGESTIONS.

References

Barkley, Z., T. Lauvaux, K. Davis, A. Deng, A. Fried, P. Weibring, D. Richter, J. Walega, J. DiGangi, and S. Ehrman (2019), Estimating methane emissions from underground coal and natural gas production in Southwestern Pennsylvania, *Geophysical Research Letters*, *46*(8), 4531-4540.

Denning, A.S. et al. 2005. Science implementation strategy for the North American Carbon Program. Report of the NACP Implementation Strategy Group of the U.S. Carbon Cycle Interagency Working Group. Washington, DC: U.S. Carbon Cycle Science Program.

Gurney, K. R., J. Liang, R. Patarasuk, Y. Song, J. Huang, and G. Roest (2020), The Vulcan version 3.0 high-resolution fossil fuel CO2 emissions for the United States, *Journal of Geophysical Research: Atmospheres*, *125*(19), e2020JD032974.

Maasakkers, J. D., D. J. Jacob, M. P. Sulprizio, A. J. Turner, M. Weitz, T. Wirth, C. Hight, M. DeFigueiredo, M. Desai, and R. Schmeltz (2016), Gridded national inventory of US methane emissions, *Environmental science & technology*, *50*(23), 13123-13133.

Oda, T., S. Maksyutov, and R. J. Andres (2018), The Open-source Data Inventory for Anthropogenic CO2, version 2016 (ODIAC2016): a global monthly fossil fuel CO2 gridded emissions data product for tracer transport simulations and surface flux inversions, *Earth Syst. Sci. Data*, *10*(1), 87-107, doi:10.5194/essd-10-87-2018.

Peischl, J., et al. (2018), Quantifying Methane and Ethane Emissions to the Atmosphere From Central and Western U.S. Oil and Natural Gas Production Regions, *Journal of Geophysical Research: Atmospheres*, *123*(14), 7725-7740, doi:https://doi.org/10.1029/2018JD028622.

Pétron, G., et al. (2020), Investigating large methane enhancements in the U.S. San Juan Basin, *Elementa: Science of the Anthropocene*, *8*(1), doi:10.1525/elementa.038.

Plant, G., E. A. Kort, C. Floerchinger, A. Gvakharia, I. Vimont, and C. Sweeney (2019), Large Fugitive Methane Emissions From Urban Centers Along the U.S. East Coast, *Geophysical Research Letters*, *46*(14), 8500-8507, doi:https://doi.org/10.1029/2019GL082635.

Smith, M. L., E. A. Kort, A. Karion, C. Sweeney, S. C. Herndon, and T. I. Yacovitch (2015), Airborne Ethane Observations in the Barnett Shale: Quantification of Ethane Flux and Attribution of Methane Emissions, *Environmental Science & Technology*, *49*(13), 8158-8166, doi:10.1021/acs.est.5b00219.

Wofsy, S.C. and R.C. Harris. 2002. The North American Carbon Program (NACP). Report of the NACP Committee of the U.S. Carbon Cycle Science Steering Group. Washington, DC: U.S. Global Change Research Program.

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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. 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. The physical mass balance of carbon serves as a quantitative constraint that can be applied to diverse observations and models. Mass balance assessments require resolution of dissimilarities in the demarcations of carbon stores and fluxes defined in different studies and disciplines. 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 concerns regarding human interactions within the carbon cycle. 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.

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 on identification of broad needs for integration and assessment across the program as a whole. The section first describes several general integration needs that are ongoing and emerging in current research and public interests. The section then highlights particular challenges and difficulties in the implementation of integration and assessment activities. Finally, several specific activities are suggested 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.

[*Note for comment and review*: The paragraphs below are intended to summarize both ongoing and emerging needs for data integration, model integration, integration of uncertainty analyses, and synthesis and assessment. Distinctions between "ongoing" and "emerging" are necessarily vague. In this draft, emerging needs are listed only in outline form, to accommodate changes that may be necessary to reflect recent developments. Suggestions are welcome.]

a. 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.

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. 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:

i. Need for improved understanding of relationships among diverse data (“My carbon is your carbon”)
   1. Across domains (ecosystems, geographic systems, human systems)
   2. Across temporal and spatial scales
   3. 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. [carbon management, mitigation protocols, economic- and social-sector-based, production-based vs. Consumption-based, MRV]

ii. Rapid improvements in capabilities for data management to improve transparency, accessibility, utility

b. Model integration

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:

- i. Improved diagnostic and comparison methods and approaches to address increasing model complexity
- ii. Overarching issues:
    1. Continuity and consistency across multiple spatial and temporal scales
    2. 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
    3. Need for balance of interests in convergence of modeling efforts
        - a. "representative" or "average" may not be best for many specific applications
        - b. need for balance between innovations and consensus
    4. Model hierarchies – e.g., space, time scales - but also need for simplified versions for access, transparency, ensembles and integrated assessments

c. Integration of uncertainty estimates and their implications

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 judgement 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.

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

d. 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 U.S. 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; King et al. 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., 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 [other examples?]). Focused syntheses and assessments have addressed important methodological needs (e.g., … [need examples, perhaps from FACE, NEON, OCO?] and modeling issues (e.g., the model inter-comparisons summarized above). Topical coordination has also drawn together communities of interest in research on carbon-cycling identified with specific human systems (e.g., energy, urban, agriculture), yielding syntheses and assessments of information of particular interest to stakeholders as well as NACP scientists (e.g., … [need specific examples here]).

Emerging synthesis and assessment needs:
1. Community support for continuing system-level syntheses; e.g., wetlands, others TBD
2. Although SOCCR3 probably not needed in this NSIP time horizon (see above), need new formats for regular timely scientific community-based assessments

3. Increasing need for improved public outreach that provides timely information in accessible formats

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 and/or breakthrough constraints and feedback concerning research and outreach needs. 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 stakeholders (both public and private-sector) are changing and becoming more urgent. Stakeholders 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 stakeholders. As stakeholders develop sources of information and analysis to meet their needs, there is a growing risk of interest-based divergence among applications that would benefit from broader perspectives.

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 stakeholder 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.

a. <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/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. 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.

b. Integration of methods to quantify uncertainties and their implications

Improved estimates of carbon-cycle uncertainties are needed by both scientists and stakeholders. 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.

c. 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.

d. 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. The carbon-cycle research community and the carbon-accounting stakeholder 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-stakeholder interactions 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-stakeholder 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 stakeholders 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, stakeholders are increasingly aware of the need for probabilistic assessments of carbon-cycle response to potential management and policy decisions. Overlapping scientist-stakeholder 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 stakeholder 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 stakeholders. Carbon storage cannot be managed in isolation from interactions with other natural resources.

References

CCSP, 2007: First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. [A. W. King, L. Dilling, G. P. Zimmerman, D. M. Fairman, R. A. Houghton, G. Marland, A. Z. Rose, and T. J. Wilbanks (eds.)]. National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, NC, USA, 242 pp.

Jacobson, A.R., Schuldt, K.N., Miller, J.B., Oda, T., Tans, P., Andrews, A., Mund, J., Ott, L., Collatz, G.J., Aalto, T. and Afshar, S., 2020. CarbonTracker CT2019. *NOAA Earth System Research Laboratory, Global Monitoring Division: Boulder, CO, USA.*

King, A.W., Dilling, L., Zimmerman, G.P., Fairman, D.M., Houghton, R.A., Marland, G., Rose, A.Z. and Wilbanks, T.J., 2007. The first state of the carbon cycle report (SOCCR): The North American carbon budget and implications for the global carbon cycle. *The first state of the carbon cycle report (SOCCR): The North American carbon budget and implications for the global carbon cycle.*

USGCRP, 2018: Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report. [Cavallaro, N., G. Shrestha, R. Birdsey, M. A. Mayes, R. G. Najjar, S. C. Reed, P. Romero-Lankao, and Z. Zhu (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 878 pp., doi: 10.7930/SOCCR2.2018.

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Chapter 3.3: Process and Attribution Studies to Uncover Mechanistic Responses to Drivers

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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. Understanding carbon cycle responses to these drivers and activities, across human, terrestrial, aquatic, and oceanic carbon cycle systems is incomplete and requires further study.

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 achieve these goals. 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 methods for process and attribution studies, the following subsections provide more specific guidance on research implementation priorities across key carbon cycle components.

3.3.1 Responses of terrestrial ecosystems 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 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. DIRT and 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 move 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 fields 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. 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 to changes in forest disturbance regimes and forest 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 requires 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. 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. 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 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), 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 stakeholders 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:

  - *a. effects of changing forest management and land use practices on forest sector carbon stocks and fluxes;*

    b. *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;*
    c. *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 to grazing management and invasive species in grasslands and shrublands

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. 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.

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 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). 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).

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 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 modelling 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, CO2 & CH4);*

   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*;
   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 ecosystems to temperature, water quality, and acidification

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 the burial, mobilization, and fate of organic carbon storage in coastal sediments and especially blue carbon in marshes, mangroves, estuaries, and seagrass meadows (McLeod et al., 2011). More comprehensive synthesis and attributions 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 state 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 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–with possible repercussions for many valuable U.S. and international commercial fisheries (Gledhill et al., 2015; Hare et al., 2016); further studies are need on shellfish as well as expanding further into assessing impacts for key crustaceans and finfish. During the mid-2000s, low pH waters associated with coastal upwelling led to reduced larval survival of Pacific oysters in some U.S. 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).

<u>Key Priorities</u>:

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). Fossil fuels dominate the region's total energy supply (DOE EIA, 2019a,b), with North America's energy consumption contributing significantly to global CO_2e emissions. The region emits approximately 17% of total global GHGs from fossil fuels and cement production (Boden et al, 2016). 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. The region also contributes significantly to worldwide energy production and energy reserves from fossil fuels spanning coal, natural gas and oil and petroleum hydrocarbon (BP 2018; DOE EIA, 2016). Trends in anthropogenic emissions of CO2e are being driven by changes in the fuel mix, such as increases in natural gas and renewables, 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).

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).

<u>Key Priorities</u>:

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.

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

References

Albright, R., Y. Takeshita, D.A. Koweek, A. Ninokawa, K. Wolfe, T. Rivlin, Y. Nebuchina, J. Young, and K. Caldeira, 2018: Carbon dioxide addition to coral reef waters suppresses net community calcification, Nature, 555, 516–519, doi:10.1038/nature25968.

Amiro, BD et al. (2010) Ecosystem carbon dioxide fluxes after disturbance in forests of North America. Journal of Geophysical Research-Biogeosciences 115. doi: 10.1029/2010jg001390.

Barton, A., G.G. Waldbusser, R.A. Feely, S.B. Weisberg, J.A. Newton, B. Hales, S. Cudd, B. Eudeline, C.J. Langdon, I. Jefferds, T. King, A. Suhrbier, and K. McLaughlin, (2015): Impacts of coastal acidification on the Pacific Northwest shellfish industry and adaptation strategies implemented in response, Oceanography, 28(2), 146–159, doi:10.5670/oceanog.2015.38.

Becknell, JM et al. (2015) Assessing Interactions Among Changing Climate, Management, and Disturbance in Forests: A Macrosystems Approach. Bioscience 65:263-274. doi: 10.1093/biosci/biu234.

Boden, T.A., G. Marland, and R.J. Andres. (2016). Global, Regional, and National Fossil-Fuel CO2 Emissions. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A. doi 10.3334/CDIAC/00001_V2016.

BP (2018), Statistical Review of World Energy, Retrieved from http://www.bp.com/statisticalreview on Friday, 29 March 2019.

Breitburg, D.L., J. Salisbury, J.M. Bernhard, W.-J. Cai, S. Dupont, S.C. Doney, K.J. Kroeker, L.A. Levin, W.C. Long, L.M. Milke, S.H. Miller, B. Phelan, U. Passow, B.A. Seibel, A.E. Todgham, and A.M. Tarrant, 2015: And on top of all that… Coping with ocean acidification in the midst of many stressors, Oceanography, 28(2), 48–61, doi:10.5670/oceanog.2015.31.

Clark, M., and D. Tilman. 2017. Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. Environmental Research Letters 12:064016.

Cohen, WB et al. (2016) Forest disturbance across the conterminous United States from 1985-2012: The emerging dominance of forest decline. Forest Ecology and Management 360:242-252. doi: 10.1016/j.foreco.2015.10.042.

Conant, RT, Cerri CEP, Osborne BB, Paustian K. 2017. Grassland management impacts on soil carbon stocks: a new synthesis. Ecol. Appl. 27(2):662–68.

DOE EIA (2016) "United States remains largest producer of petroleum and natural gas hydrocarbons" Today in Energy, [Retreived from https://www.eia.gov/todayinenergy/detail.php?id=26352 on Friday, 29 March 2019].

DOE EIA (2019a) "International Data." U.S. Energy Information Administration. [Retreived from http://www.eia.gov/beta/international/ on Thursday, 28 March 2019].

DOE EIA (2019b) "U.S. States and Energy Estimates, U.S. Overview", [Retrieved from https://www.eia.gov/state/ on Wednesday, 27 March 2019].

Domke G., Williams C. A., Birdsey R., Coulston J., Finzi A., Gough C., Haight B., Hicke J., Janowiak M., de Jong B., Kurz W. A., Lucash M., Ogle S., Olguín-Álvarez M., Pan Y., Skutsch M., Smyth C., Swanston C., Templer P., Wear D., Woodall C. W. 2018. Forests. In: Cavallaro N., Shrestha G., Birdsey R., Mayes M. A., Najjar R. G., Reed S. C., Romero-Lankao P., Zhu Z., eds. Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report. Washington, DC: U.S. Global Change Research Program: 365-398. https://doi.org/10.7930/SOCCR2.2018.Ch9.

Fahey, TJ et al. (2010) Forest carbon storage: ecology, management, and policy. Frontiers in Ecology and the Environment 8:245-252. doi: 10.1890/080169.

Gledhill, D.K., M.M. White, J. Salisbury, H. Thomas, I. Mlsna, M. Liebman, B. Mook, J. Grear, A.C. Candelmo, R.C. Chambers, C.J. Gobler, C.W. Hunt, A.L. King, N.N. Price, S.R. Signorini, E. Stancioff, C. Stymiest, R.A. Wahle, J.D. Waller, N.D. Rebuck, Z.A. Wang, T.L. Capson, J.R. Morrison, S.R. Cooley, and S.C. Doney, 2015: Ocean and coastal acidification off New England and Nova Scotia, Oceanography, 28(2), 182–197, doi:10.5670/oceanog.2015.41.

Goetz, SJ et al. (2012) Observations and assessment of forest carbon dynamics following disturbance in North America. Journal of Geophysical Research-Biogeosciences 117. doi: G02022, 10.1029/2011jg001733.

Govaerts, B., N. Verhulst, A. Castellanos-Navarrete, K. D. Sayre, J. Dixon, and L. Dendooven. 2009. Conservation Agriculture and Soil Carbon Sequestration: Between Myth and Farmer Reality. Critical Reviews in Plant Sciences 28:97-122.

Hare, J.A., W.E. Morrison, M.W. Nelson, M.M. Stachura, E.J. Teeters, R.B. Griffis, M.A. Alexander, J.D. Scott, L. Alade, R.J. Bell, A.S. Chute, K.L. Curti, T.H. Curtis, D. Kircheis, J.F. Kocik, S.M. Lucey, C.T. McCandless, L.M. Milke, D.E. Richardson, E. Robillard, H.J. Walsh, M.C. McManus, K.E. Marancik, and C.A. Griswold, 2016: A vulnerability assessment of fish and invertebrates to climate change on the northeast U.S. continental shelf, PLoS ONE, 11(2), e0146756. doi:10.1371/journal.pone.0146756.

Heath, LS, Smith JE, Skog KE, Nowak DJ, Woodall CW (2011) Managed Forest Carbon Estimates for the US Greenhouse Gas Inventory, 1990-2008. Journal of Forestry 109:167-173.

Hurtt, GC, Thomas RQ, Fisk JP, Dubayah RO, Sheldon SL (2016) The Impact of Fine-Scale Disturbances on the Predictability of Vegetation Dynamics and Carbon Flux. Plos One 11:11. doi: 10.1371/journal.pone.0152883.

Keenan, T. F., and C. A. Williams (2018), The Terrestrial Carbon Sink, Annu. Rev. Environ. Resour., 43(1), 219-243, doi:10.1146/annurev-environ-102017-030204.

Klumpp, K, Fontaine S, Attard E, Le Roux X, Gleixner G, Soussana J-F. 2009. Grazing triggers soil carbon loss by altering plant roots and their control on soil microbial community. J. Ecol. 97(5):876–85.

Kopittke, P. M., R. C. Dalal, D. Finn, and N. W. Menzies, 2017: Global changes in soil stocks of carbon, nitrogen, phosphorus, and sulphur as influenced by long-term agricultural production. Global Change Biology, 23(6), 2509-2519, doi: 10.1111/gcb.13513.

Kroeker, K.J., R.L. Kordas, R. Crim, I.E. Hendriks, L. Ramajo, G.S. Singh, C.M. Duarte, and J.-P. Gattuso, 2013: Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming, Global Change Biology, 19, 1884–1896, doi: 10.1111/gcb.12179.

Machmuller, M. B., M. G. Kramer, T. K. Cyle, N. Hill, D. Hancock, and A. Thompson, 2015: Emerging land use practices rapidly increase soil organic matter. Nature Communicatons, 6, 6995, doi: 10.1038/ncomms7995.

Marcotullio, P. J., L. Bruhwiler, S. Davis, J. Engel-Cox, J. Field, C. Gately, K. R. Gurney, D. M. Kammen, E. McGlynn, J. McMahon, W. R. Morrow, III, I. B. Ocko, and R. Torrie, 2018: Chapter 3: Energy systems. In Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report [Cavallaro, N., G. Shrestha, R. Birdsey, M. A. Mayes, R. G. Najjar, S. C. Reed, P. Romero-Lankao, and Z. Zhu (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 110-188, https://doi.org/10.7930/SOCCR2.2018.Ch3.

McKinley, D. C., and J. M. Blair, 2008: Woody plant encroachment by Juniperus virginiana in a mesic native grassland promotes rapid carbon and nitrogen accrual. Ecosystems, 11(3), 454-468, doi: 10.1007/s10021-008-9133-4.

McLeod, E., G.L. Chmura, S. Bouillon, R. Salm, M. Björk, C.M. Duarte, C.E. Lovelock, W.H. Schlesinger, and B.R. Silliman, 2011: A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2, Front. Ecol. Environ., 9(10): 552–560, doi:10.1890/110004.

Montes, F., R. Meinen, C. Dell, A. Rotz, A. N. Hristov, J. Oh, G. Waghorn, P. J. Gerber, B. Henderson, H. P. S. Makkar, and J. Dijkstra. 2013. SPECIAL TOPICS — Mitigation of methane and nitrous oxide emissions from animal operations: II. A review of manure management mitigation options1. Journal of Animal Science 91:5070-5094.

Montgomery, D. R., 2007: Soil erosion and agricultural sustainability. Proceedings of the National Academy of Sciences USA, 104(33), 13268-13272, doi: 10.1073/pnas.0611508104.

Naito, AT, Cairns DM. 2011. Patterns and processes of global shrub expansion. Prog. Phys. Geogr. 35(4):423–42.

Najjar, R. G., Herrmann, M., Alexander, R., Boyer, E. W., Burdige, D. J., Butman, D., et al (2018) Carbon budget of tidal wetlands, estuaries, and shelf waters of eastern North America. Global Biogeochemical Cycles, 32, 389–416, https://doi.org/10.1002/2017GB005790.

Ogle, S. M., F. J. Breidt, and K. Paustian, 2005: Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. Biogeochemistry, 72(1), 87-121, doi: 10.1007/s10533-004-0360-2.

Owensby, CE, Ham JM, Auen LM. 2006. Fluxes of CO2 from grazed and ungrazed tallgrass prairie. Rangel. Ecol. Manag. 59(2):111–27.

Paustian, K., J. Lehmann, S. Ogle, D. Reay, G. P. Robertson, and P. Smith, 2016: Climate-smart soils. Nature, 532(7597), 49-57, doi: 10.1038/nature17174.

Peters, C. J., J. Picardy, A. F. Darrouzet-Nardi , J. L. Wilkins, T. S. Griffin, and G. W. Fick (2016) Carrying capacity of U.S. agricultural land: Ten diet scenarios. Elem Sci Anth 4:116.

Regnier, P., Friedlingstein, P., Ciais, P., Mackenzie, F. T., Gruber, N., Janssens, I. A., et al. (2013) Anthropogenic perturbation of the carbon fluxes from land to ocean. Nature Geoscience, 6(8), 597–607, https://doi.org/10.1038/ngeo1830.

Reimer, J. J., Wang, H., Vargas, R., & Cai, W.-J. (2017) Multidecadal fCO2 increase along the United States southeast coastal margin. Journal of Geophysical Research: Oceans, 122, 10,061–10,072, https://doi.org/10.1002/2017JC013170.

Rosi, A., P. Mena, N. Pellegrini, S. Turroni, E. Neviani, I. Ferrocino, R. Di Cagno, L. Ruini, R. Ciati, D. Angelino, J. Maddock, M. Gobbetti, F. Brighenti, D. Del Rio, and F. Scazzina. 2017. Environmental impact of omnivorous, ovo-lacto-vegetarian, and vegan diet. Scientific Reports 7:6105.

Smith P et al. (2016) Global change pressures on soils from land use and management. Global Change Biology 22:1008-1028. doi: 10.1111/gcb.13068.

Steinfeld, H., and P. Gerber. 2010. Livestock production and the global environment: Consume less or produce better? Proceedings of the National Academy of Sciences 107:18237-18238.

Strong, A.L., K.J. Kroeker, L.T. Teneva, L.A. Mease, and R.P. Kelly (2014) Ocean acidification 2.0: managing our changing coastal ocean chemistry, BioScience, 64, 581–592, doi:10.1093/biosci/biu072.

Wang, Z. G., T. Hoffmann, J. Six, J. O. Kaplan, G. Govers, S. Doetterl, and K. Van Oost, 2017: Human-induced erosion has offset one-third of carbon emissions from land cover change. Nature Climate Change, 7(5), 345, doi: 10.1038/Nclimate3263.

Williams CA, Gu H, MacLean R, Masek JG, Collatz GJ (2016) Disturbance and the carbon balance of US forests: A quantitative review of impacts from harvests, fires, insects, and droughts. Global and Planetary Change 143:66-80. doi: 10.1016/j.gloplacha.2016.06.002.

Williams, C. A., M. E. Vanderhoof, M. Khomik, and B. Ghimire (2014), Post-clearcut dynamics of carbon, water and energy exchanges in a midlatitude temperate, deciduous broadleaf forest environment, Global Change Biology, 20, 992-1007.

****** INTERNAL DRAFT ******

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Chapter 3.4. Predictions: Model Development, Evaluation and Prediction

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3.4 Introduction

The 2011 North American Carbon Program 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.

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), 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.

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 time-scales, 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 (Riaho 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) quantify 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 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, and a 2018 report by the U. S. National Academy of Science offers four “negative emissions technologies” as a proposed set of such actions; 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. 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 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 understanding 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 observed 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 up 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). When incorporated into process models, respiratory temperature acclimation can have a large impact on terrestrial carbon storage (Lombardozzi 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, 2012; 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 C 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 through space. Different factors/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 C 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 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 C 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 Quere 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., 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 WEO, 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., NOx 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, granular activity data is 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 CH4, 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 approach provide the basis for predictive modeling of LOAC at seasonal, decadal, and centennial time scales.

References

Abramowitz, G. (2012), Towards a public, standardized, diagnostic benchmarking system for land surface models, *Geosci. Model Dev.*, *5*(3), 819-827, doi:10.5194/gmd-5-819-2012.

Anav, A., P. Friedlingstein, M. Kidston, L. Bopp, P. Ciais, P. Cox, C. Jones, M. Jung, R. Myneni, and Z. Zhu (2013), Evaluating the Land and Ocean Components of the Global Carbon Cycle in the CMIP5 Earth System Models, *Journal of Climate*, *26*(18), 6801-6843, doi:10.1175/jcli-d-12-00417.1.

Andres, R. J., et al. (2012), A synthesis of carbon dioxide emissions from fossil-fuel combustion, *Biogeosciences*, *9*(5), 1845-1871, doi:10.5194/bg-9-1845-2012.

Arora, V. K., et al. (2013), Carbon-concentration and carbon-climate feedbacks in CMIP5 Earth System Models, *Journal of Climate*, *26*, 5289-5314.

Blyth, E., D. B. Clark, R. Ellis, C. Huntingford, S. Los, M. Pryor, M. Best, and S. Sitch (2011), A comprehensive set of benchmark tests for a land surface model of simultaneous fluxes of water and carbon at both the global and seasonal scale, *Geosci. Model Dev.*, *4*(2), 255-269, doi:10.5194/gmd-4-255-2011.

Bonan, G. B., & Doney, S. C. (2018). Climate, ecosystems, and planetary futures: The challenge to predict life in Earth system models. Science-New York Then Washington-, 359(6375), eaam8328–11. http://doi.org/10.1126/science.aam8328.

Bonan, G. B., Hartman, M. D., Parton, W. J., & Wieder, W. R. (2012). Evaluating litter decomposition in earth system models with long-term litterbag experiments: an example using the Community Land Model version 4 (CLM4). Global Change Biology, n/a–n/a. http://doi.org/10.1111/gcb.12031.

Booth, B. B. B., C. D. Jones, M. Collins, I. J. Totterdell, P. M. Cox, S. Sitch, C. Huntingford, R. A. Betts, G. R. Harris, and J. Lloyd (2012), High sensitivity of future global warming to land carbon cycle processes, *Environ. Res. Lett.*, *7*(2), 024002, doi:10.1088/1748-9326/7/2/024002.

Ciais, P., et al. (2013), Carbon and Other Biogeochemical Cycles, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, B. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Ciais, P., et al. (2020), Empirical estimates of regional carbon budgets imply reduced global soil heterotrophic respiration, *National Science Review*, *8*(2), doi:10.1093/nsr/nwaa145.

Collier, N., F. M. Hoffman, D. M. Lawrence, G. Keppel-Aleks, C. D. Koven, W. J. Riley, M. Mu, and J. T. Randerson (2018), The International Land Model Benchmarking (ILAMB) System: Design, Theory, and Implementation, *Journal of Advances in Modeling Earth Systems*, *10*(11), 2731-2754, doi:https://doi.org/10.1029/2018MS001354.

Cox, P. M., D. Pearson, B. B. Booth, P. Friedlingstein, C. Huntingford, C. D. Jones, and C. M. Luke (2013), Sensitivity of tropical carbon to climate change constrained by carbon dioxide variability, *Nature*, *494*(7437), 341-344, doi:10.1038/nature11882.

Davis, S. J., et al. (2018), Net-zero emissions energy systems, *Science, 360*(6396), eaas9793, doi:10.1126/science.aas9793.

Dietze, M. C. (2014), Gaps in knowledge and data driving uncertainty in models of photosynthesis, *Photosynth. Res.*, *119*(1), 3-14, doi:10.1007/s11120-013-9836-z.

Dietze, M. C. (2017), Prediction in ecology: a first-principles framework, *Ecological Applications*, *27*(7), 2048-2060, doi:https://doi.org/10.1002/eap.1589.

Dietze, M. C., D. S. Lebauer, and R. Kooper (2013), On improving the communication between models and data, *Plant, Cell & Environment*, *36*(9), 1575-1585, doi:https://doi.org/10.1111/pce.12043.

Dietze, M. C., A. Fox, L. M. Beck-Johnson, J. L. Betancourt, M. B. Hooten, C. S. Jarnevich, T. H. Keitt, M. A. Kenney, C. M. Laney, L. G. Larsen, H. W. Loescher, C. K. Lunch, B. C. Pijanowski, J. T. Randerson, E. K. Read, A. T. Tredennick, R. Vargas, K. C. Weathers, E. P. White (2018), Iterative near-term ecological forecasting: Needs, opportunities, and challenges, Proc. Nat. Acad. Sci., 115(7):1 424–1432, doi:10.1073/pnas.1710231115.

Eyring, V., et al. (2016), ESMValTool (v1.0) – a community diagnostic and performance metrics tool for routine evaluation of Earth system models in CMIP, *Geosci. Model Dev.*, *9*(5), 1747-1802, doi:10.5194/gmd-9-1747-2016.

Fatichi, S., S. Leuzinger, and C. Körner (2014), Moving beyond photosynthesis: from carbon source to sink-driven vegetation modeling, *New Phytologist*, *201*(4), 1086-1095, doi:10.1111/nph.12614.

Fischer, G., F. Nachtergaele, S. Prieler, H.T. van Velthuizen, L. Verelst, D. Wiberg, 2008. Global Agro-ecological Zones Assessment for Agriculture (GAEZ 2008). IIASA, Laxenburg, Austria and FAO, Rome, Italy.

Friedlingstein, P., M. Meinshausen, V. K. Arora, C. D. Jones, A. Anav, S. K. Liddicoat, and R. Knutti (2014), Uncertainties in CMIP5 Climate Projections due to Carbon Cycle Feedbacks, *Journal of Climate*, *27*(2), 511-526, doi:10.1175/jcli-d-12-00579.1.

Friedlingstein, P., M. W. Jones, M. O'sullivan, R. M. Andrew, J. Hauck, G. P. Peters, W. Peters, J. Pongratz, S. Sitch, and C. L. Quéré (2019), Global carbon budget 2019, *Earth System Science Data*, *11*(4), 1783-1838.

Fuss, S., et al. (2018), Negative emissions—Part 2: Costs, potentials and side effects, *Environ. Res. Lett.*, *13*(6), 063002, doi:10.1088/1748-9326/aabf9f.

Gately, C. K., and L. R. Hutyra (2017), Large Uncertainties in Urban-Scale Carbon Emissions, *Journal of Geophysical Research: Atmospheres*, *122*(20), 11,242-211,260, doi:https://doi.org/10.1002/2017JD027359.

Gurney, K.R., Romero-Lankao, P., Seto, K.C., Hutyra, L.R., Duren, R., Kennedy, C., Grimm, N.B., Ehleringer, J.R., Marcotullio, P., Hughes, S. and Pincetl, S., 2015. Climate change: Track urban emissions on a human scale. *Nature News*, *525*(7568), p.179.

Hashimoto, S., Carvalhais, N., Ito, A., Migliavacca, M., Nishina, K., and Reichstein, M. (2015) Global spatiotemporal distribution of soil respiration modeled using a global database, Biogeosciences, 12, 4121–4132, https://doi.org/10.5194/bg-12-4121-2015.

Hayes, D. J., et al. (2012), Reconciling estimates of the contemporary North American carbon balance among terrestrial biosphere models, atmospheric inversions, and a new approach for estimating net ecosystem exchange from inventory-based data, *Global Change Biology*, *18*(4), 1282-1299, doi:https://doi.org/10.1111/j.1365-2486.2011.02627.x.

Huntzinger, D. N., et al. (2020), Evaluation of simulated soil carbon dynamics in Arctic-Boreal ecosystems, *Environ. Res. Lett.*, *15*(2), 025005, doi:10.1088/1748-9326/ab6784.

Hurtt, G. C., et al. (2020), Harmonization of global land use change and management for the period 850–2100 (LUH2) for CMIP6, *Geosci. Model Dev.*, *13*(11), 5425-5464, doi:10.5194/gmd-13-5425-2020.

IEA (2018), World Energy Outlook 2018, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2018.

IPCC, 2018: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)]. In Press.

Kondo, M., et al. (2020), State of the science in reconciling top-down and bottom-up approaches for terrestrial CO2 budget, *Global Change Biology*, *26*(3), 1068-1084, doi:https://doi.org/10.1111/gcb.14917.

Konings, A. G., Bloom, A. A., Liu, J., Parazoo, N. C., Schimel, D. S., and Bowman, K. W. (2019) Global satellite-driven estimates of heterotrophic respiration, Biogeosciences, 16, 2269–2284, https://doi.org/10.5194/bg-16-2269-2019.

Koven, C. D., Riley, W. J., Subin, Z. M., Tang, J. Y., Torn, M. S., Collins, W. D., et al. (2013). The effect of vertically resolved soil biogeochemistry and alternate soil C and N models on C dynamics of CLM4. Biogeosciences, 10(11), 7109–7131. http://doi.org/10.5194/bg-10-7109-2013.

Koven, C. D., Lawrence, D. M., & Riley, W. J. (2015). Permafrost carbon−climate feedback is sensitive to deep soil carbon decomposability but not deep soil nitrogen dynamics. Proceedings of the National Academy of Sciences of the United States of America, 201415123–6. http://doi.org/10.1073/pnas.1415123112.

Kumar, S. V., C. D. Peters-Lidard, J. Santanello, K. Harrison, Y. Liu, and M. Shaw (2012), Land surface Verification Toolkit (LVT) – a generalized framework for land surface model evaluation, *Geosci. Model Dev.*, *5*(3), 869-886, doi:10.5194/gmd-5-869-2012.

Lawrence, D. M., et al. (2019), The Community Land Model Version 5: Description of New Features, Benchmarking, and Impact of Forcing Uncertainty, *Journal of Advances in Modeling Earth Systems*, *11*(12), 4245-4287, doi:https://doi.org/10.1029/2018MS001583.

Le Quéré, C., R. M. Andrew, P. Friedlingstein, S. Sitch, J. Hauck, J. Pongratz, P. A. Pickers, J. I. Korsbakken, G. P. Peters, and J. G. Canadell (2018), Global carbon budget 2018, *Earth System Science Data*, *10*(4), 2141-2194.

Levis, S., A. Badger, B. Drewniak, C. Nevison, and X. Ren (2018), CLMcrop yields and water requirements: avoided impacts by choosing RCP 4.5 over 8.5, *Climatic Change*, *146*(3), 501-515, doi:10.1007/s10584-016-1654-9.

Lombardozzi, D., G. B. Bonan, and D. W. Nychka (2014), The emerging anthropogenic signal in land–atmosphere carbon-cycle coupling, *Nature Climate Change*, *4*(9), 796-800, doi:10.1038/nclimate2323.

Lombardozzi, D. L., Bonan, G. B., Smith, N. G., Dukes, J. S., & Fisher, R. A. (2015). Temperature acclimation of photosynthesis and respiration: A key uncertainty in the carbon cycle-climate feedback. Geophysical Research Letters, 42(20), 8624–8631. http://doi.org/10.1002/2015GL065934.

Lombardozzi, D. L., Smith, N. G., Cheng, S. J., Dukes, J. S., Sharkey, T. D., Rogers, A., et al. (2018). Triose phosphate limitation in photosynthesis models reduces leaf photosynthesis and global terrestrial carbon storage. Environmental Research Letters, 13(7), 074025–10. http://doi.org/10.1088/1748-9326/aacf68.

Lovenduski, N. S., and G. B. Bonan (2017), Reducing uncertainty in projections of terrestrial carbon uptake, *Environ. Res. Lett.*, *12*(4), 044020.

Matthews, H. D., A. J. Weaver, K. J. Meissner, N. Gillett, and M. Eby (2004), Natural and anthropogenic climate change: incorporating historical land cover change, vegetation dynamics and the global carbon cycle, *Climate Dynamics*, *22*(5), 461-479.

O'Neill, B. C., et al. (2017), The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century, *Global Environmental Change*, *42*, 169-180, doi:https://doi.org/10.1016/j.gloenvcha.2015.01.004.

Radeloff, V. C., E. Nelson, A. J. Plantinga, D. J. Lewis, D. Helmers, J. Lawler, J. Withey, F. Beaudry, S. Martinuzzi, and V. Butsic (2012), Economic-based projections of future land use in the conterminous United States under alternative policy scenarios, *Ecological Applications*, *22*(3), 1036-1049.

Raiho, A. M., M. Dietze, A. Dawson, C. Rollinson, J. Tipton, and J. McLachlan (2020), Determinants of Predictability in Multi-decadal Forest Community and Carbon Dynamics, *BioRxiv*.

Reichstein, M., G. Camps-Valls, B. Stevens, M. Jung, J. Denzler, and N. Carvalhais (2019), Deep learning and process understanding for data-driven Earth system science, *Nature*, *566*(7743), 195-204.

Rogers, A., Medlyn, B. E., Dukes, J. S., Bonan, G., Caemmerer, von, S., Dietze, M. C., et al. (2017). A roadmap for improving the representation of photosynthesis in Earth system models. New Phytologist, 213(1), 22–42. http://doi.org/10.1111/nph.14283.

Schuur, E. A. G., McGuire, A. D., Schädel, C., Grosse, G., Harden, J. W., Hayes, D. J., et al. (n.d.). Climate change and the permafrost carbon feedback. Nature, 520, 171 EP –.

Seto, K. C., B. Güneralp, and L. R. Hutyra (2012), Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools, *Proceedings of the National Academy of Sciences*, *109*(40), 16083-16088.

Sherwin, E. D., M. Henrion, and I. M. Azevedo (2018), Estimation of the year-on-year volatility and the unpredictability of the United States energy system, *Nature Energy*, *3*(4), 341-346.

Slot, M., & Winter, K. (2017). In situ temperature response of photosynthesis of 42 tree and liana species in the canopy of two Panamanian lowland tropical forests with contrasting rainfall regimes. New Phytologist. http://doi.org/10.1111/nph.14469.

Smith, N. G., & Dukes, J. S. (2012). Plant respiration and photosynthesis in global-scale models: incorporating acclimation to temperature and CO2. Global Change Biology, 19(1), 45–63. http://doi.org/10.1111/j.1365-2486.2012.02797.x.

Wenzel, S., P. M. Cox, V. Eyring, and P. Friedlingstein (2016), Projected land photosynthesis constrained by changes in the seasonal cycle of atmospheric CO 2, *Nature*, *538*(7626), 499-501.

Wieder, W. R., Bonan, G. B., & Allison, S. D. (2013). Global soil carbon projections are improved by modelling microbial processes. Nature Climate Change. http://doi.org/10.1038/nclimate1951http://doi.org/10.1038/nclimate1951.

Woodard, D. L., Davis, S. J. & Randerson, J. T. (2018). Economic carbon cycle feedbacks may offset additional warming from natural feedbacks. Proceedings of the National Academy of Sciences 116, 759-764. https://www.pnas.org/content/116/3/759.

****** INTERNAL DRAFT ******
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Chapter 3.5: Communication, Coordination and Decision Support

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Question: How can we develop science and models that provide data, projections, and understanding that are relevant, credible and useful for decision makers at the local, state and national scales?

3.5.1 Communication 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).

Since its founding, the NACP charged itself with a roughly decadal State of the Carbon Cycle Report that takes stock of current understanding and trends. The NACP and its participating community of scientists have been supported by multiple Federal agencies emphasizing a focus on changes to the carbon cycle. To ensure the plan is effective, the *Science Leadership Group (SLG)* works to communicate among government program managers, independent research groups, and multiple institutions not affiliated to the government. The people with whom this knowledge is shared must value—and to some degree internalize—its importance. For if the public does not value the benefits of science, funding will go elsewhere, and decisions will be made using whatever information might be at hand (Gropp 2018). This chapter focuses on three communication goals for the NACP in the coming decades.

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 stakeholders. These barriers could 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 stakeholders.

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 stakeholders (both policy makers and the private sector) to determine what information they need, when its needed and linking this to published research would help improve the dialog and utilization of scientific research.

Innovative partnerships between researchers, funding entities, and beneficiary stakeholders could include public-private partnerships, such as the new collaboration between Google and the UN Environment division, in efforts to track specific environment-related development targets with a user-friendly Google front-end. The Global Carbon Project, the Long Term Ecological Research (LTER) program, NASA’s Earth Observing Program (EOS), National Ecological Observatory Network (NEON), the Ocean Carbon & Biogeochemistry and other programs provide great examples of additional and alternative communication activities that have impact and reach beyond that of the NACP. Similarly, the NACP could engage with high profile organizations with access to government and public policy decision makers. Organizations that use social media (e.g. Facebook, LinkedIn) and print media organizations (New York Times, Washington Times, etc) could engage with the NACP in their efforts to communicate broad findings to a broad spectrum of stakeholders.

Stakeholders are both providers of bottom-up information and also users of that information. Major private corporations and cities can benefit from NACP efforts by contributing data, and by then accessing analysis of how their carbon impacts compare with other corporations, cities and industries, or how their impacts contribute to national accounts. NACP can facilitate inter-stakeholder communication by integrating the information from many stakeholders 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 need training on more constructive engagement with decision makers could also be useful. For scientists, there 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 in making carbon cycle observations, models and tool development directed toward policy applications, the NACP can reduce barriers to scientists’ participation in stakeholder engagement. The NACP can use incentives, clearly articulated selection criteria and funding opportunities to reduce barriers to participation.

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

A critical objective of the NACP is to produce bottom-up inventories, linking these to observations, connecting these observations to models, and communicating the resulting data uncertainties to both the scientific and stakeholder communities. This work has the potential to greatly improve the prioritization, formulation and verification of policies meant to reduce carbon emissions. By integrating across these scales, the NACP can improve policy makers’ ability to understand the impact of policies on emissions.

Whereas past efforts have achieved significant advancement in detailed inventories, observations, and models, future efforts will require a systems-approach to provide actionable information for decision making. We need to know the systematic effects of uncertainty on decision making, both direct and indirect, of government policy, corporate investment, economic growth, and consumer behavior. This information must connect each participant in the system to the broader carbon cycle effects of their individual decisions. 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. Focusing on confidence estimates, as opposed to uncertainties, shifts the perception of the discussion from something of weakness to a topic of strength and optimism. “Uncertainty” puts decision making and policy people into an insecure state of mind, therefore a focus on confidence estimates is a better bet.

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 the stakeholder community. 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 “sciencey” and are not relatable for decision makers. This is an immediate deterrent as they feel the information is not tailored to them. Carbon cycle scientists should engage with scientific expertise from psychology, engineering and political science, among other disciplines, to effectively communicate their uncertainty information.

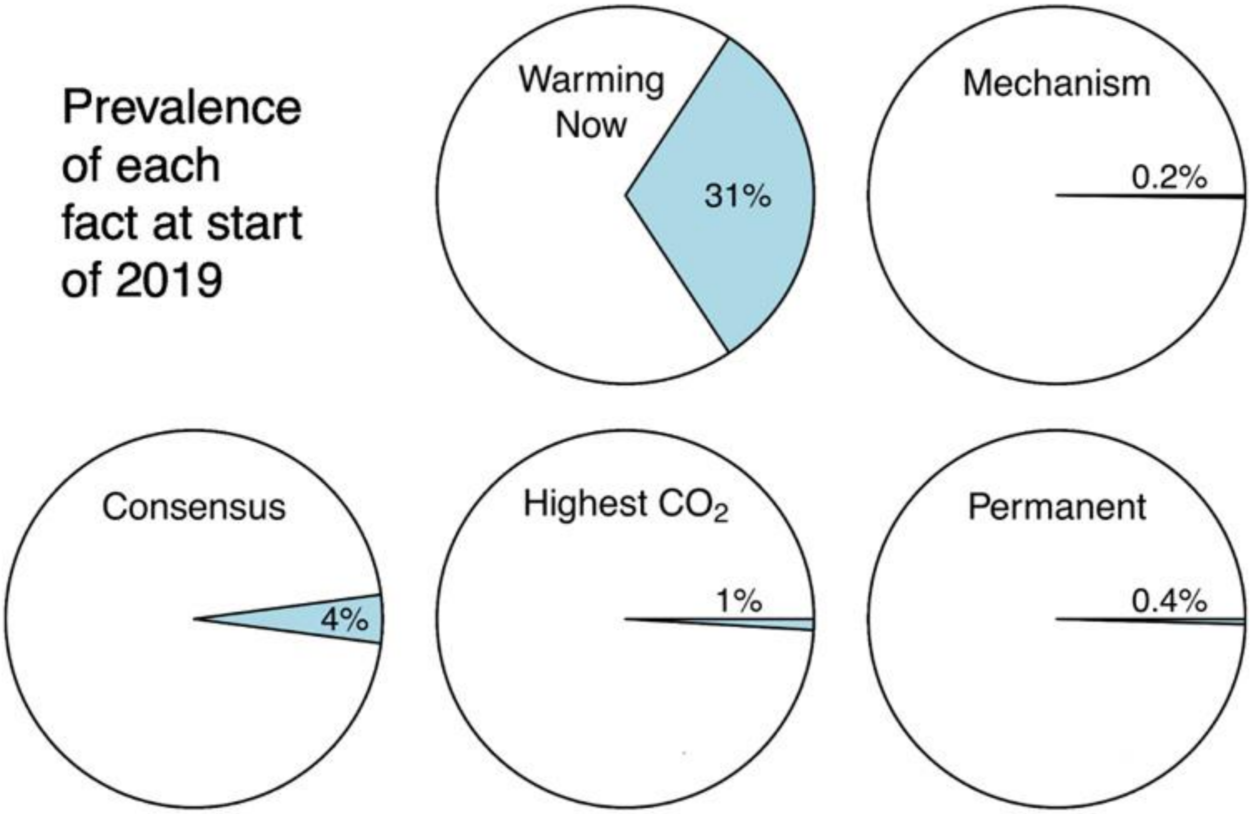


Figure 1. The percentage of climate change articles in the New York Times since 1980 that mention five basic facts about global warming: the climate is warming now, the mechanism is through the burning of fossil fuels, there is more CO_2 in the atmosphere than there has been for hundreds of thousands of years, and that these changes are effectively permanent. (Graphic by David Romps, UC Berkeley).

3.5.1.3 Participate in the science of communicating science

NACP needs to engage with 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 (NAS, 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 stakeholders at a variety of levels. Although scientific research does not have a simple cause-and-effect relationship with improved societal outcomes, 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 stakeholders. 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 stakeholders 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 stakeholders.*
4. *Facilitate inter-stakeholder communication by placing stakeholder-originated 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 regardless of the sophistication of the user.

3.5.2.1 Engagement with boundary organizations to co-produce knowledge

Public policy and decision making must become increasingly dependent on expertise and expert knowledge. 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 these 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 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) has 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. Forests are also at the root of House Republican leaders' push to capture carbon dioxide from the atmosphere. Recently, they unveiled plans for a series of climate bills, among which is a proposal to grow more trees "for the purpose of sequestering carbon. **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.

The NACP can contribute to ensuring that there is funding to support the engagement of scientists with policy makers, decision makers and others who may use their science. Co-production of knowledge through identifying user information demands and working with the users from the start of the scientific process allows scientists to develop results that are both usable and socially robust, and contributes to users being more engaged and invested in the science. User-driven science thrives when institutions shift priorities to meet user needs and set reward structures accordingly. By ensuring that there is funding for improved science communication across multiple institutions, formats, and objectives, the NACP can ensure that these efforts are prioritized and valued within its research agenda.

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 efforts.

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 stakeholders and policy makers – people who 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, stakeholder mapping is required for the institutions and individuals involved in investment, production, consumption, management, and policy making that substantially impact the carbon cycle. Each stakeholder should be characterized in terms of their connections to other stakeholders, their direct emissions and emissions decisions, 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 a boundary organization working at the metropolitan scale is the Decision Center for a Desert City (DCDC), whose mission is to advance knowledge about decision making under uncertainty in the context of water sustainability and urban climate change adaptation. By working across multiple institutions at different levels, the DCDC is focused on improving decision making across the Colorado River Basin and the cities that rely upon its water in a warming and drying climate.

NACP science can be instrumental in understanding how the climate is changing and helping the cities in the Basin craft appropriate responses to these changes.

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 national-level boundary organization is the Consortium for Science, Policy and Outcomes (CSPO) that focuses on translating science for 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).

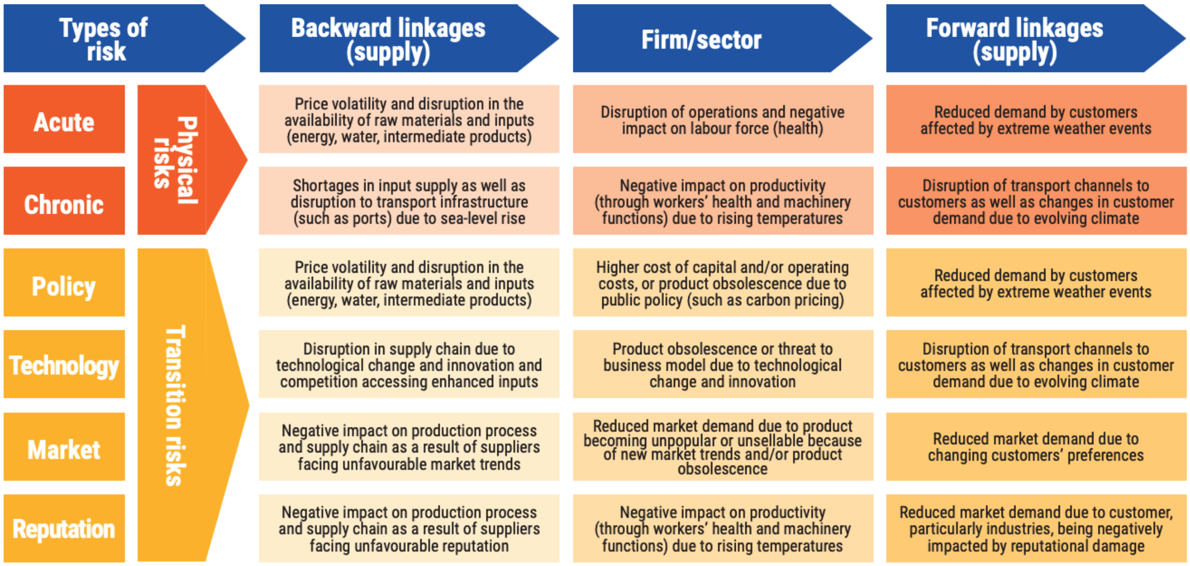
3.5.2.3 Engagement that produces research Outputs that are relevant, credible, and legitimate for Decision Makers

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. 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 2. shows the variety of both physical and transition risks small and medium sized businesses face from climate change, which involve both supply chain as well as direct threats to business functioning via demand and distribution impacts. 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 planned for. Research funding should incentivize the inclusion of user needs assessments in projects.

<u>Key priorities:</u>

1. *The NACP can develop a database of effective boundary institutions for different research themes, datasets, and stakeholders.*
2. *Encourage and train researchers to identify potential stakeholders and decision makers for each model, research output and relevant insight that may emerge from their research.*

3. *NACP should 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 speak to one another and to enable engagement with stakeholder communities 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 integrates various 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.

The 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 across research and decision making

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 stakeholders 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 contribute to these campaigns 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 US Carbon Cycle Science Program 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 U.S. 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.

Additional activities of the CMS 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. These 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 U.S. 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. These space-time constraints don’t often match with earth system and integrated assessment models so some level of downscaling should be involved to enhance 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. Because the NASA CMS is a funding program, it cannot engage with international scientists and with scientists who were not successful in obtaining funding. The two programs have similar goals with different constraints and scope.

<u>Key Priorities for Coordination</u>:

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 multiple agencies and institutions seeking to inform policy 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 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 government 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 alters 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.

3.5.4.1 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 X) 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.

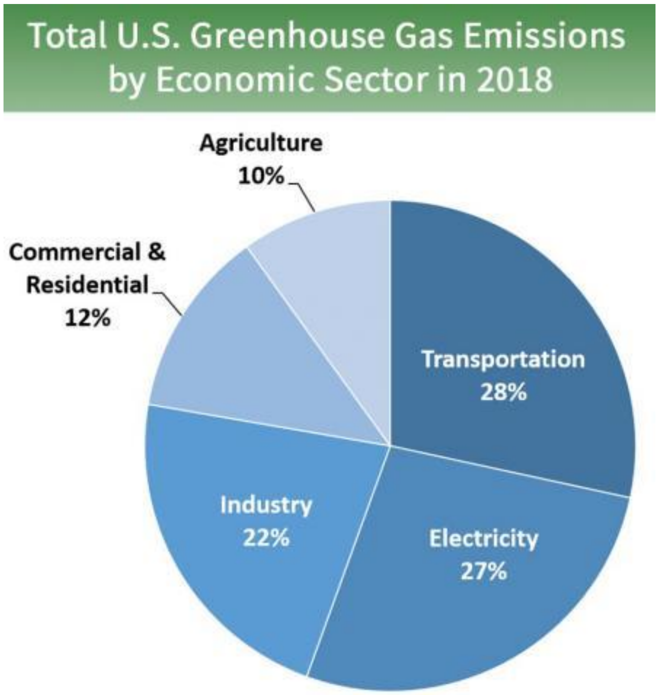


Figure X. Total Emissions in 2018 = 6,677 Million Metric Tons of CO_2equivalent. Percentages may not add up to 100% due to independent rounding. Land use, land-use change, and forestry in the United States is a net sink and offsets approximately 12 percent of these greenhouse gas emissions, this emissions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

Monitoring carbon emissions includes both top down and bottom-up analysis and modelling, 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 only reduce overall 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. Without this end-to-end approach, appropriate policies cannot be developed that actually will reduce emissions substantially. This kind of science is typically beyond what the NACP works on, but will be essential for development of appropriate and effective policies.

3.5.4.2 Engaging across temporal and spatial scales 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 estimations 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 stakeholder 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, 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.

3.5.4.3 Communicating uncertainty in information and monitoring systems

Uncertainty quantification is a critical aspect to 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 4.5.1.2 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.

3.5.4.4 Managing risk to governments, institutions and individuals

Risks from climate change to society, government, institutions and individuals is profound 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 (*Guid. to Clim. Chang. Adapt. Cities*, 2011), biodiversity (Bhuiyan et al., 2018) and human health (McMichael et al., 2006). 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 November 2018 National Climate Assessment report, 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 (Hayhoe et al., 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 should be supported and managed at the Federal level. Federal leadership of the 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 needs to accelerate decision making and support in the coming decade.

3.6 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.

References

Bhuiyan, M.A., Jabeen, M., Zaman, K., Khan, A., Ahmad, J., Hishan, S.S., 2018. The impact of climate change and energy resources on biodiversity loss: Evidence from a panel of selected Asian countries. Renew. energy 117, 324–340.

Brown, M.E., Antle, J.M., Backlund, P., Carr, E.G., Easterling, W.E., Walsh, M.K., Ammann, C., Attavanich, W., Barrett, C.B., Bellemare, M.F., Dancheck, V., Funk, C., Grace, K., Ingram, J.S.I., Jiang, H., Maletta, H., Mata, T., Murray, A., Ngugi, M., Ojima, D., O’Neill, B., Tebaldi, C., 2015. Climate Change, Global Food Security, and the U.S. Food System. USDA Technical Document, Washington DC. https://doi.org/10.7930/J0862DC7

Bui, B., De Villiers, C., 2017. Business strategies and management accounting in response to climate change risk exposure and regulatory uncertainty. Br. Account. Rev. 49, 4–24.

Cohen, S.A., Bose, S., Guo, D., DeFrancia, K., Berger, O., Filiatraut, B., Miller, A.C., Loman, M., Qiu, W., Zhang, C., 2014. The Growth of Sustainability Metrics (Sustainability Metrics White Paper Series: 1 of 3).

Davies, D.K., Brown, M.E., Murphy, K.J., Michael, K.A., Zavodsky, B.T., Stavros, E.N., Caroll, M.L., 2017. Workshop on Using NASA Data for Time-Sensitive Applications. IEEE Geosci. Remote Sens. Mag. 5. https://doi.org/10.1109/MGRS.2017.2729278

Dawson, R.J., Thompson, D., Johns, D., Wood, R., Darch, G., Chapman, L., Hughes, P.N., Watson, G.V.R., Paulson, K., Bell, S., Gosling, S.N., Powrie, W., Hall, J.W., 2018. A systems framework for national assessment of climate risks to infrastructure. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. https://doi.org/10.1098/rsta.2017.0298

Funk, C., Rainie, L., Page, D., 2015. Public and scientists’ views on science and society. Pew Research Center 2015.

Gropp, R.E., 2018. Engaging Decision-Makers: Opportunities and Priorities for Biological Science Organizations. Bioscience 68, 643–648. https://doi.org/10.1093/biosci/biy082

Guide to Climate Change Adaptation in Cities, 2011. , Guide to Climate Change Adaptation in Cities. https://doi.org/10.1596/27396

Guston, D.H., 2001. Boundary organizations in environmental policy and science: an introduction.

Hausfather, Z., Peters, G.P., 2020. Emissions--the ‘business as usual’story is misleading.

Hayhoe, K., Wuebbles, D.J., Easterling, D.R., Fahey, D.W., Doherty, S., Kossin, J.P., Sweet, W. V, Vose, R.S., Wehner, M.F., 2018. Our Changing Climate. Impacts, Risks, and Adaptation in the United States: The Fourth National Climate Assessment, Volume II.

Huang, W., Dolan, K., Swatantran, A., Johnson, K., Tang, H., O’Neil-Dunne, J., Dubayah, R., Hurtt, G., 2019. High-resolution mapping of aboveground biomass for forest carbon monitoring system in the Tri-State region of Maryland, Pennsylvania and Delaware, USA. Environ. Res. Lett. 14, 95002.

Jones, S.A., Fischhoff, B., Lach, D., 1999. Evaluating the science-policy interface for climate change research. Clim. Change 43, 581–599.

Kim, S.K., 2020. The Economic Effects of Climate Change Adaptation Measures: Evidence from Miami-Dade County and New York City. Sustainability 12, 1097.

McMichael, A.J., Woodruff, R.E., Hales, S., 2006. Climate change and human health: present and future risks. Lancet 367, 859–869.

Michalak, A.M., Jackson, R., Marland, G., Sabine, C.L., 2011. A US carbon cycle science plan. Citeseer.

Mills-Knapp, S., Bourdeau, E., Falco, G., Resler, C., Tovar, H., Zoegall, S., 2011. Climate change adaptation and sustainable design at the port authority of New York and New Jersey. Earth Institute, Columbia Univ. New York, NY, USA.

NAS, 2017. Communicating science effectively: A research agenda. National Academies Press, Washington D.C.

Rosenzweig, C., Arnell, N.W., Ebi, K.L., Lotze-Campen, H., Raes, F., Rapley, C., Smith, M.S., Cramer, W., Frieler, K., Reyer, C.P.O., others, 2017. Assessing inter-sectoral climate change risks: the role of ISIMIP. Environ. Res. Lett. 12, 10301.

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A.C., Müller, C., Arneth, A., Boote, K.J., Folberth, C., Glotter, M., Khabarov, N., others, 2014. Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proc. Natl. Acad. Sci. 111, 3268–3273.

Sachs, J.D., Schmidt-Traub, G., Mazzucato, M., Messner, D., Nakicenovic, N., Rockström, J., 2019. Six transformations to achieve the sustainable development goals. Nat. Sustain. 2, 805–814.

Stanley, B.W., 2017. Policy Approaches to Transparent Urban Development in Phoenix, in: Transparent Urban Development. Springer, pp. 239–285.

Tak, S., Toet, A., Van Erp, J., 2015. Public understanding of visual representations of uncertainty in temperature forecasts. J. Cogn. Eng. Decis. Mak. 9, 241–262.

Vitousek, S., Barnard, P.L., Fletcher, C.H., Frazer, N., Erikson, L., Storlazzi, C.D., 2017. Doubling of coastal flooding frequency within decades due to sea-level rise. Sci. Rep. https://doi.org/10.1038/s41598-017-01362-7

West, T.O., Brown, M.E., Duren, R.M., Ogle, S.M., Moss, R.H., 2013. Definition, capabilities and components of a terrestrial carbon monitoring system. Carbon Manag. 4. https://doi.org/10.4155/cmt.13.36

West, T.O., Gurwick, N., Brown, M.E., Duren, R., Mooney, S., Paustian, K., McGlynn, E., Malone, E., N. Hultman, N., Ocko, I.B., Rosenblatt, A., 2018. Chapter 18: Carbon cycle science in support of decision making, in: Cavallaro, N., Shrestha, G., Birdsey, R., Mayes, M.A., Najjar, R., Reed, S., Romero-Lankao, P., Zhu, Z. (Eds.), Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/SOCCR2.2018.Ch18.

Weyant, J., 2017. Some Contributions of Integrated Assessment Models of Global Climate Change. Rev. Environ. Econ. Policy 11, 115–137. https://doi.org/10.1093/reep/rew018.

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Chapter 4. Partnerships and Collaborations: Institutional and International

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The work of the NACP relies on a wide net of institutional and international contributions. 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 Program resilience to potential variations in funding priorities and availability.

NACP science contributes to global understanding of the carbon cycle by engaging with stakeholders 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 government. 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) 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 U.S. Federal competitive research funding for carbon cycle science, there are ongoing challenges for establishing and maintaining 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 requiring intensive or long-term investment and coordination.

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 that uncover key mechanisms. 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 from initial investments into long-term, sustained networks. Examples include LTER, AmeriFlux, ABoVE, and MsTMIP. Synthesis activities help to maintain and renew these communities and significantly expand their impact, often with limited cost.

Science Communities of Practice

NACP 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 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 community of practice and to buffer the challenges of cross-institutional, transdisciplinary, and potentially transnational collaboration. The roles of the NACP Coordinator, the NACP Science Leadership Group, and the commitment to holding Open Science Meetings all help to maintain and expand the NACP Community. Also, reporting activities, such as the State of the Carbon Cycle Report and the National Climate Assessment, generate continued interest in and commitment to our multi-institutional community. More work could be done, with the assistance US Carbon Cycle Science Program and others, to enhance connections between NACP and communities with similar or overlapping research interests, such as the US Ocean Biology and Biogeochemistry Program (OCB), the Global Carbon Project, (GCP), and others. Bridging to adjacent programs such as these will add value to all by enhancing programmatic coordination, realizing strategic synergies, exchanging ideas, elevating impact, and facilitating new initiatives that cut across scales and boundaries.

Tri-federal collaborations across the US, Canada, and Mexico

Participation in NACP has been largely from individuals at US institutions, although research has not been limited to carbon cycling within US borders. This is a historical artefact, as a result of NACP having been established by US Federal agencies participating in the US Carbon Cycle Science Program. Soon after NACP was founded, program managers from Federal agencies in the US, Canada, and México set up CarboNA, whose goal was to establish greater cohesion across North America in the fields of carbon pool and greenhouse gas flux dynamics and of 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 group has become essentially defunct. Despite the fact that there are likely still many impediments to coordination at the governmental level, there is an opportunity for NACP to become broader in its community composition by making and strengthening 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 and Mexican institutions, finding meaningful ways to build a trans-national community that supports the needs and interests of carbon cycle science researchers throughout North America.

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. For example, North American efforts would benefit from coordination with similar international efforts such as the Integrated Carbon Observing System in Europe and other regional efforts such as the International Long Term Ecological Network present in Canada, Mexico and the USA. 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 and aircraft measurement networks that complement and anchor remote sensing data, including the use of best practices and common standards and data formats. These efforts will ensure comparability and will narrow interoperability barriers (i.e., conceptual, technological, organizational, cultural) among regional networks (Vargas et al. 2017).

With support and guidance from the NACP Office and the U.S. Carbon Cycle Science Program Office, the NACP 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), the World Climate Research Program (WCRP), the Integrated Carbon Observing System (ICOS), the Integrated Global Greenhouse Gas Information System (IG3IS), and FLUXNET/AmeriFlux/MexFlux, Coastal Carbon Research Coordination Network (CCRCN) and the Permafrost Carbon Network.

Private sector and stakeholders

In support of the NACP vision and DEI needs, the NACP would likely benefit from exploring partnerships with stakeholders and private entities with whom the NACP has traditionally not interacted in the past. These relationships would expand the accessibility, useability, exchange, use and visibility of the science, tools and products among all involved collaborators while also creating opportunities for developing innovative products to advance common goals and meet stakeholder needs.

For instance, the National Indian Carbon Coalition (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 may wish to catalyze expanded collaborative activities with 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 this important set of decision makers and stakeholders.

References

Brown, M.E., Ihli, M., Hendrick, O., Delgado-Arias, S., Escobar, V.M., Griffith, P., 2016. Social network and content analysis of the North American Carbon Program as a scientific community of practice. Social Networks 44, 226–237. https://doi.org/10.1016/j.socnet.2015.10.002

McCarthy, M. I., B. Ramsey, J. Phillips, and M. H. Redsteer, 2018: Chapter 7: Tribal lands. In Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report [Cavallaro, N., G. Shrestha, R. Birdsey, M. A. Mayes, R. G. Najjar, S. C. Reed, P. Romero-Lankao, and Z. Zhu (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 303-335, https://doi.org/10.7930/SOCCR2.2018.Ch7.

Vargas, R., et al. (2017), Enhancing interoperability to facilitate implementation of REDD+: case study of Mexico, *Carbon Management*, *8*(1), 57-65, doi:10.1080/17583004.2017.1285177.

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, MCI, and 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 almost 450 that have been archived and are publicly, as well as almost 300 more under development (as of Feb. 2021) in the NACP Database. This diverse collection of data products include 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 FIA, USDA NASS, and NSF NEON and LTER Networks, and BCO-DMO. 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 TE program and carbon cycle & ecosystem 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.

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 stakeholders. However, the very large volume of data and the distribution of this data across multiple data repositories 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 stakeholders 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 Findable, Accessible, Interoperable, and Reusable (FAIR) data (Wilkinson et al., 2016), 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 Modelling 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.

5.2.3 Data discovery and access

Different agencies have invested a fair amount of efforts 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 in 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., 2020). 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 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. Funding agencies need to ensure that research projects have an appropriate level of resources dedicated to data management. 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.

References

Behnke, J., Mitchell, A. and Ramapriyan, H., 2019. NASA's Earth Observing Data and Information System – Near-Term Challenges. Data Science Journal, 18(1), p.40. DOI: http://doi.org/10.5334/dsj-2019-040

Ciais, P., Dolman, A. J., Bombelli, A., Duren, R., Peregon, A., Rayner, P. J., Miller, C., Gobron, N., Kinderman, G., Marland, G., Gruber, N., Chevallier, F., Andres, R. J., Balsamo, G., Bopp, L., Bréon, F.-M., Broquet, G., Dargaville, R., Battin, T. J., Borges, A., Bovensmann, H., Buchwitz, M., Butler, J., Canadell, J. G., Cook, R. B., DeFries, R., Engelen, R., Gurney, K. R., Heinze, C., Heimann, M., Held, A., Henry, M., Law, B., Luyssaert, S., Miller, J., Moriyama, T., Moulin, C., Myneni, R. B., Nussli, C., Obersteiner, M., Ojima, D., Pan, Y., Paris, J.-D., Piao, S. L., Poulter, B., Plummer, S., Quegan, S., Raymond, P., Reichstein, M., Rivier, L., Sabine, C., Schimel, D., Tarasova, O., Valentini, R., Wang, R., van der Werf, G., Wickland, D., Williams, M., and Zehner, C. 2014. Current systematic carbon-cycle observations and the need for implementing a policy-relevant carbon observing system, Biogeosciences, 11, 3547–3602, https://doi.org/10.5194/bg-11-3547-2014

Cook, R.B., Y. Wei, L.A. Hook, S.K.S Vannan, J.J. McNelis. 2018. Preserve: Protecting Data for Long-Term Use. In: F. Recknagel, W. Michener (eds) Ecological Informatics. Springer, Cham. https://doi.org/10.1007/978-3-319-59928-1_6

Gurney, K.R., J. Liang, R. Patarasuk, Y. Song, J. Huang, and G. Roest. 2020. Vulcan: High-Resolution Hourly Fossil Fuel CO2 Emissions in USA, 2010-2015, Version 3. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1810

Michener, W., S. Allard, A. Budden, R. Cook, K. Douglass, M. Frame, St Kelling, R. Koskela, C. Tenopir, D. Vieglais. 2012. Participatory design of DataONEEnabling cyberinfrastructure for the biological and environmental sciences. Ecol. Inform., 11 (2012), pp. 5-15. https://doi.org/10.1016/j.ecoinf.2011.08.007

Moroni, D F, Ramapriyan, H, Peng, G, Hobbs, J, Goldstein, J C, Downs, R R, Wolfe, R, Shie, C-L, Merchant, C J, Bourassa, M, Matthews, J L, Cornillon, P, Bastin, L, Kehoe, K, Smith, B, Privette, J L, Subramanian, A C, Brown, O, and Ivánová, I 2019 Understanding the Various

Perspectives of Earth Science Observational Data Uncertainty. Figshare. https://doi.org/10.6084/m9.figshare.10271450

Peng, G., Downs, R. R., Lacagnina, C., Ramapriyan, H., Ivánová, I., Moroni, D. F., Wei, Y., et al. (2020, December 15). Call to Action for Global Access to and Harmonization of Quality Information of Individual Earth Science Datasets. https://doi.org/10.31219/osf.io/nwe5p

Ramapriyan, H, Peng, G, Moroni, D, and Shie, C-L 2017 Ensuring and Improving Information Quality for Earth Science Data and Products. D-Lib Magazine, 23, https://doi.org/10.1045/july2017-ramapriyan

Tilmes, C., Fox, P., Ma, X., McGuinness, D.L., Privette, A.P., Smith, A., Waple, A., Zednik, S., Zheng, J.G.: Provenance representation for the national climate assessment in the global change information system. IEEE Trans. Geosci. Remote Sens. 51(11), 5160–5168 (2013). https://doi.org/10.1109/TGRS.2013.2262179

Wilkinson, M., Dumontier, M., Aalbersberg, I. et al. The FAIR Guiding Principles for scientific data management and stewardship. Sci Data 3, 160018 (2016). https://doi.org/10.1038/sdata.2016.18