A U.S. Carbon Cycle Science Plan

Anna M. Michalak, Robert B. Jackson, Gregg Marland, Christopher Sabine,
and the Carbon Cycle Science Working Group[1]

December 10, 2010

Review Draft – Not for citation

[1] Bob Anderson, Debbie Bronk, Kenneth Davis, Ruth DeFries, Scott Denning, Lisa Dilling, Rob Jackson, Andy Jacobson, Steve Lohrenz, Gregg Marland, David McGuire, Galen McKinley, Anna Michalak, Charles Miller, Berrien Moore, Dennis Ojima, Brian O'Neill, Jim Randerson, Steve Running, Christopher Sabine, Brent Sohngen, Pieter Tans, Peter Thornton, Steve Wofsy, Ning Zeng

Table of Contents

Executive Summary

CHAPTER 1: Introduction

Carbon is an integral part of the Earth system and the building block of life. Its presence in the atmosphere as carbon dioxide (CO_2) and methane (CH_4) is critical to maintaining a habitable climate. It plays a major role in the chemistry, physics, and biology of the oceans. Carbon is currently also the dominant element in human energy use, forming the basis of coal, oil, and natural gas – hydrocarbon compounds derived from plants that removed CO_2 from the atmosphere hundreds of millions of years ago. The continual transport and transformation of carbon in the Earth's atmosphere, rivers and oceans, soils, rocks, living organisms, and human systems is what we call the global carbon cycle.

Human activities have substantially altered the Earth's natural carbon cycle. Human use of energy has grown exponentially in the last century, and the extraction and combustion of fossil fuels have replaced society's early reliance on renewable energy sources such as biomass, wind and running water. Fossil carbon, carbon that was removed from the "active pools" of the earth system (plants, fresh water systems, oceans, soils, and the atmosphere) and buried in the Earth's interior, is being returned to the active carbon cycle. As a result, carbon dioxide is building up in the atmosphere and in the oceans. In addition, human use of land for activities such as farming, forestry, and urbanization has resulted in a gradual release of soil and plant carbon, further increasing the amount of carbon in the atmosphere and oceans.

Overall, the mixing ratio (concentration) of CO_2 in the atmosphere has increased to approximately 390 parts per million (ppm) compared to about 280 ppm for approximately 11,000 years prior to the industrial revolution, and the concentration is now increasing by an average of almost 2 ppm per year (IPCC 2007). Methane concentrations have increased even more dramatically - to 1.8 ppm now from 0.8 ppm prior to the industrial revolution.

These changes in atmospheric greenhouse gas concentrations are affecting the Earth in at least two important ways. First, our climate is changing. The Earth is 0.8°C warmer than it was a hundred years ago, and the most recent decade was the warmest in at least a century (e.g., Arndt et al. 2010). Other aspects of the climate system, such as the amounts and timing of rainfall, are also changing in amplitude and distribution. The impacts of this anthropogenic climate change are widespread and increasingly significant (e.g., Jones et al. 2009). Second, increased atmospheric CO_2 has direct effects on both terrestrial and aquatic ecosystems. On land, increasing CO_2 can alter plant productivity and biodiversity as well as the competitive success of weeds and other species. In the oceans, the pH of ocean surface waters has already decreased by about 0.1 since the beginning of the industrial revolution, with a decrease of approximately 0.0018 yr^{-1} observed over the last quarter century (e.g. Caldeira and Wickett, 2005; Bates, 2007). The current and future decline in carbonate ion concentrations as a consequence of ocean acidification imperils many calcifying marine organisms (including corals, shellfish and marine plankton) that form their skeletons or other hard parts out of calcium carbonate (e.g., Fabry et al, 2008).

Understanding the Earth's carbon cycle is both a challenging intellectual problem and an urgent societal need. The impacts of human-caused changes in the global carbon cycle will be felt on the Earth for hundreds to thousands of years. Direct observations and process-based understanding of the global carbon cycle are needed to determine how the cycle is being modified, what the responses are to those modifications, and how best to develop sound climate change mitigation and adaptation strategies.

The most widely-known evidence for the changing global carbon cycle is the record of the atmospheric CO_2 concentration from Mauna Loa in Hawaii; measurements started in the 1950s by the late C. D. Keeling and continue to the present day. Today, scientists are documenting the increase in atmospheric greenhouse gases at over a hundred sites around the world. These data, combined with economic data for fossil fuel use, show that roughly half of the CO_2 that has been emitted into the atmosphere through fossil fuel burning and land-use change has accumulated in the atmosphere. The remaining half has been removed by the Earth's oceans and biosphere. The institutions and processes governing CO_2 emissions and uptake are not fully understood, and they do not allow us to anticipate perfectly how CO_2 emissions will change in the future. The trajectory of the future carbon cycle is poorly constrained, and our understanding of sources and sinks of CH_4 lags behind our understanding for CO_2.

Recognition of the need for better understanding and coordinated research on the global carbon cycle led to the development of the first U.S. Carbon Cycle Science Plan about a decade ago (Sarmiento and Wofsy, 1999). This document set forth a plan for terrestrial, atmospheric and oceanic measurements, manipulative experiments, and earth-system modeling to improve our understanding of the current carbon cycle and our ability to predict its future behavior. The 1999 Science Plan was primarily focused on quantifying the atmospheric, oceanic, and terrestrial carbon sinks, in an effort to balance the global carbon budget. One particular focus was quantifying the magnitude of the North American carbon sink.

Based in part on the goals of the 1999 Science Plan, the carbon cycle science community has, over the last decade, developed much better global- and regional-scale carbon budgets. One important set of science questions today focuses on understanding the processes controlling the exchange between the active and fossil carbon pools. To predict how the carbon cycle might change in the future, and, ultimately, what the consequences of those changes will be, we need to develop a better understanding of the causes and drivers of change. This mechanistic focus is somewhat different from that of the 1999 Science Plan, but is essential for meeting the needs of policy makers and society at large.

Several issues drive the need for a new U.S. Carbon Cycle Science Plan (hereafter the "Plan") and highlight some new research priorities. With greenhouse-gas concentrations rising rapidly, active management of the global carbon cycle is increasingly urgent, but management without understanding can be ineffective or even counter-productive. Carbon-cycle research should thus be pursued with attention to the efficacy and environmental consequences of carbon management policies, strategies, and technologies. Humans are an integral part of the carbon cycle, both through influences on "natural" systems, managed ecosystems, and direct emissions of greenhouse gases. Study of the human elements of the carbon cycle should therefore be more thoroughly integrated into the research agenda. A third need for new research recognizes that ecosystems, species, and natural resources are increasingly affected by rising greenhouse gas concentrations, climate change, and carbon-management decisions. Research focused on important thresholds or tipping points in the carbon cycle is sorely needed. Finally, decisions about the carbon cycle will inevitably be made with imperfect knowledge. We need a better understanding of uncertainly in all aspects of the global carbon cycle, and improved ways of reducing uncertainties and conveying those uncertainties to policy and decision makers, as well as society at large.

Our reassessment of the U.S. carbon cycle science priorities described here was initiated by the U.S. Carbon Cycle Interagency Working Group (CCIWG) and Carbon Cycle Science Steering Group (CCSSG) in 2008 (see Appendix A for the charge to the committee). The new Plan is intended to provide guidance for U.S. research efforts on the global carbon cycle for the next decade. A committee of 25 scientists was assembled to achieve this goal (see Appendix B). The committee included members from the diverse research communities that have traditionally comprised the U.S. carbon cycle science program, along with members from research areas needed to expand the research effort. Once formed, the committee extended wide outreach in an effort to garner input from a broad research community. These outreach activities are detailed in Appendix C.

In outlining a research agenda for the next decade, we have chosen to preserve the hierarchal structure adopted in the 1999 Carbon Cycle Science Plan. Chapter 2 provides a brief history of the 1999 Science Plan, progress made since that plan was prepared, and the context in which the new Plan has now been developed. We next articulate overriding questions that guide the new research agenda in Chapter 3.

Within this agenda, we identify specific goals that define achievable objectives for the next decade and beyond (Chapter 4), and outline the primary research elements that we believe must be pursued to achieve the stated goals (Chapter 5). The elements are the basic research components needed for developing the science.

In Chapters 6 and 7, we turn to some barriers and opportunities for the success of the Plan. In Chapter 6 we characterize the complex interdisciplinary realm in which carbon-cycle science needs to be pursued, and the collaborations and cooperation necessary for success. We also recognize in Chapter 6 that U.S.-based research needs to be pursued in an environment that is cooperative, supportive, and interactive with research being pursued throughout an increasingly interdependent world. Finally, in Chapter 7, we summarize our vision of the priorities for ongoing research and offer our recommendations for the scope and scale of needed research.

Our new research plan emphasizes the long-lived, carbon-based greenhouse gases carbon dioxide and methane and the other major pools and fluxes of the global carbon cycle. Certain non-greenhouse-gases, including carbon monoxide (CO) and ratios of oxygen to nitrogen (O2:N2), provide important constraints on the global carbon cycle and are part of the plan in that context only. Throughout this document, we emphasize the importance of an integrated system to collect and maintain the essential data that drive scientific understanding.

CHAPTER 2: History and Context

2.1 The 1999 U.S. Carbon Cycle Science Plan

In 1998-1999, a working group of 16 carbon-cycle researchers prepared a science plan to focus and coordinate carbon-cycle research in the United States. The intent was "to develop a strategic and optimal mix of essential components, which include sustained observations, modeling, and innovative process studies, coordinated to make the whole greater than the sum of its parts" (Sarmiento and Wofsy, 1999). In the decade since the 1999 science plan was published, carbon-cycle researchers have worked to improve carbon-observing networks and to coordinate research projects addressing the goals of the 1999 plan. Considerable progress has been made over the past decade, but constraints on funding and time have prevented some parts of the plan from being fully realized. Furthermore, carbon-cycle research over the last decade has targeted new issues that were not highlighted or foreseen in the original 1999 plan. For instance, concerns about how the human perturbation of the carbon cycle might affect the overall distribution of carbon in the active carbon pools have intensified, and there is increasing public policy interest in possibilities for mitigating human impacts.

Given these many changes in the last decade, there is a clear need to update the carbon cycle research plan for the coming decade. The research community needs to re-examine research and policy needs, prioritize current and future research directions, and outline the funding necessary to meet these needs. Without a thoughtful Plan, it is not possible to clearly articulate priorities, to coordinate activities among researchers and research sponsors, and to provide appropriate resources for research.

Under the auspices of the U.S. research agencies' Carbon Cycle Interagency Working Group and the U.S. Carbon Cycle Science Program's Science Steering Group, a working group of 25 scientists within the carbon cycle science community was formed in late 2008. Their charge (see Appendix A) was to review the 1999 Science Plan and to develop a new strategy for carbon-cycle research conducted by U.S. researchers in the coming decade. The Plan needed to be global in scope and collaborative in scale, building partnerships with many groups around the world, but the focus is on the U.S. research community and the work sponsored by U.S. funding agencies. From the beginning, the vision clearly needed to be established in such a way as to be inclusive of, and collaborative with, a greater spectrum of the social sciences and with public policy needs.

The 1999 Science Plan posed two fundamental science questions to frame compelling priorities at the time: 1) What has happened to the carbon dioxide that has already been emitted by human activities (past anthropogenic CO_2)? and 2) What will be the future atmospheric CO_2 concentration trajectory resulting from both past and future emissions? These two questions focused on the past, present, and future CO_2 concentrations. To address these questions, the 1999 Plan articulated five program goals:

Goal 1: Quantify and understand the Northern Hemisphere terrestrial carbon sink

Goal 2: Quantify and understand the uptake of anthropogenic CO_2 in the ocean

Goal 3: Determine the impacts of past and current land use on the carbon budget

Goal 4: Provide greatly improved projections of future atmospheric concentrations of CO_2

Goal 5: Develop the scientific basis for societal decisions about management of CO_2 and the carbon cycle.

These questions and goals guided the U.S. carbon cycle research program into the 2000s.

2.2 Implementation of the 1999 Science Plan

After the 1999 U.S. Carbon Cycle Science Plan was completed, two major national programs were created to address the goals of the plan. These programs were specifically designed to promote and facilitate large interdisciplinary research projects required to meet the goals. The North American Carbon Program (NACP) is aimed primarily at addressing Goal 1, and the Ocean Carbon and Climate Change (OCCC) program was developed to address Goal 2. Agencies also made significant investments in other projects aimed at the other Carbon Cycle Science Plan goals. The 1999 plan formed the basis for the Carbon Cycle chapter of the broader 2003 Strategic Plan for the Climate Change Science Program (Climate Change Science Program, 2003), where the five goals of the 1999 U.S. Carbon Cycle Science Plan (Sarmiento and Wofsy 1999) were refined into 6 specific questions. In addition, the two overriding questions of the 1999 plan were updated to:

- How large and variable are the dynamic reservoirs and fluxes of carbon within the Earth system, and how might carbon cycling change be managed in future years, decades, and centuries?

- What are our options for managing carbon sources and sinks to achieve an appropriate balance of risk, cost, and benefit to society?

The *North American Carbon Program Science Plan* was published in 2002 (Wofsy and Harriss, 2002). The plan was prepared by the NACP Committee of the U.S. Carbon Cycle Science Steering Group, at the request of the Agencies of the U.S. Global Change Research Program, to plan for "carbon cycle research focused on measuring and understanding sources and sinks of CO_2, CH_4, and CO in North America and adjacent oceans." This was followed by *The Science Implementation Strategy for the North American Carbon Program* (Denning et al. 2005), written after a broad community of scientists involved in carbon cycle studies conducted a multiyear process of scoping, prioritizing, and planning for a comprehensive program of interdisciplinary research. The NACP is organized around four questions:

1. What is the carbon balance of North America and adjacent oceans? What are the geographic patterns of fluxes of CO_2, CH_4, and CO? How is the balance changing over time? ("Diagnosis")

2. What processes control the sources and sinks of CO_2, CH_4, and CO, and how do the controls change with time? ("Attribution/Process")

3. Are there potential surprises (could sources increase or sinks disappear)? ("Prediction")

4. How can we enhance and manage long-lived carbon sinks ("sequestration"), and provide resources to support decision makers? ("Decision support")

Research activities were recommended and prioritized within each major area to contribute to an integrated and well-tested system for understanding, observing, and predicting carbon fluxes over North America and adjacent ocean regions, and for providing timely and useful information to policymakers based on the results.

An integrated, multi-agency implementation strategy for oceanic observations and research was developed in parallel with the NACP to determine how much carbon dioxide is being taken up by the ocean at the present time and how climate change will affect the future behavior of the carbon sink. Within the broader goals outlined by the 1999 Science Plan, the *Ocean, Carbon and Climate Change: An Implementation Strategy for U.S. Ocean Carbon Research* (Doney et al., 2004) document highlighted four fundamental science questions to address:

1. What are the global inventory, geographic distribution, and temporal evolution of anthropogenic CO_2 in the oceans?
2. What are the magnitude, spatial pattern, and variability of air-sea CO_2 flux?

3. What are the major physical, chemical, and biological feedback mechanisms and climate sensitivities for ocean organic and inorganic carbon storage?

4. What is the scientific basis for ocean carbon mitigation strategies?

In 2005, the U.S. Carbon Cycle Science Program established the Ocean Carbon and Climate Change (OCCC) program and the OCCC Scientific Steering Group (OCCC-SSG), with a specific charge to address multi-agency ocean carbon coordination. In February of 2006 the NSF, NASA and NOAA decided to combine several related ocean programs including OCCC, the Surface Ocean Lower Atmosphere Study (SOLAS) and the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) under one umbrella organization called the Ocean Carbon and Biogeochemistry (OCB) program to more broadly address issues of marine biogeochemistry (including carbon) and associated ecology. The OCCC-SSG members are a sub-group of the OCB-SSC and do not meet separately.

Through the coordinated efforts of U.S. funding agencies, the NACP and OCB programs have made great progress in addressing the first two goals of the 1999 Science Plan. Despite additional investments made by agencies, the lack of coordinated interdisciplinary national programs resulted in less progress on the latter goals, particularly Goal 5 (developing the scientific basis for societal decisions about management of CO_2 and the carbon cycle), but also to some extent Goal 3 (determining the impacts of past and current land use on the carbon budget) and Goal 4 (providing greatly improved projections of future atmospheric concentrations of CO_2)

.The committee on the Human Dimensions of Global Change of the National Research Council (Stern 2002) hosted a workshop in 2001 that highlighted the need for greater research on the human dimensions of the carbon cycle. The group concluded that although the 1999 Science Plan "notes the critical role of human activities in perturbing the carbon cycle, it does not include any research on these activities. The U.S. government's carbon cycle research activity has not yet integrated the relevant fields of the social and behavioral sciences." The committee wrote of building bridges between the natural and social sciences to produce the understanding necessary to "inform public decisions." They distinguished "human activities that affect the carbon cycle" and "human activities that respond to the carbon cycle."

2.3 Other relevant developments since the 1999 Science Plan

Since publication of the 1999 carbon cycle plan, several documents have revised components of the U.S. Climate Change Research Program and highlighted the need for a new U.S. Carbon Cycle Science Plan. Collectively these documents provide insight into the research needs and the effectiveness of the program as described in this Plan.

The Strategic Plan for the Climate Change Science Program (Climate Change Science Program, 2003) was the first comprehensive update of a strategic plan for the U.S. Global Change Research Program (1989). Five research goals were identified to focus research and to synthesize knowledge around broad strategic questions. The six research questions for Global Carbon Cycle (see Chapter 7 of the *Strategic Plan*) were derived from the five goals recommended by the research community in *A U.S. Carbon Cycle Science Plan* (Sarmiento and Wofsy 1999).

In 2007, the National Research Council presented its first review of the progress since the U.S. Climate Change Science Program/U.S. Global Change Research Program was established in 2002 (NRC, 2007).

The NRC evaluated and assessed the strengths and weaknesses of the entire program, identifying areas where progress had not met expectations. In regard to the Global Carbon Cycle questions (7.1-7.6) from the 2003 *Strategic Plan for the Climate Change Science Program*, the report declared that good progress had been made in documenting and understanding the current carbon sources and sinks. The North American carbon budget had been recently assessed (SOCCR, 2007), but improvements in the observation and modeling approaches were needed to reduce uncertainties (Q 7.1). Focused research efforts and the synthesis of decades of observations reduced the uncertainties associated with the size of the ocean carbon sink, but significant uncertainties in ocean carbon processes remained (Q 7.2). On the subject of land-use change and the carbon cycle, the report concluded that good progress had been made in understanding the historical relationships between land use and the carbon balance, but great uncertainties in future land management scenarios limited predictive capability (Q 7.3). Although fair progress had been made in linking changes in regional and global rates of carbon dioxide accumulation to climatic anomalies, understanding of the processes underlying some of these relationships was poor and limited our ability to predict factors that will dominate in the future (Q 7.4). Prediction of future fossil fuel emissions as well as carbon sources and sinks associated with future changes in land management were limited by the lack of involvement of stakeholder communities (Q 7.5). Informing carbon management was a new area of emphasis for the carbon cycle research element and had not yet made adequate progress (Q 7.6).

Also in 2007, the Climate Change Science Program and Subcommittee on Global Change Research published *The First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle* (SOCCR, 2007). The report provided a synthesis and integration of the current knowledge of the North American carbon budget and its context within the global carbon cycle.

In 2008, a *Revised Research Plan for the U.S. Climate Change Science Program* provided an update to the 2003 *Strategic Plan for the Climate Change Science Program* to take into account the advances in the science and changes in societal needs, draw on the program's long range planning process, and comply with the terms of the 1990 Global Change Research Act (Climate Change Science Program, 2008). That document highlighted the progress and accomplishments of the carbon cycle research elements over the previous four years and encouraged the continued development of future plans.

In 2009, the National Research Council published the report *Restructuring Federal Climate Research to Meet the Challenges of Climate Change* (NRC, 2009). This report describes a new framework for generating the scientific-socioeconomic knowledge needed to understand and respond to climate change. It identified six priorities for a restructured U.S. Global Change Research Program (USGCRP) that would help develop a more robust knowledge-base and support informed decisions. The document recommended reorganizing the USGCRP around integrated scientific-societal issues; establishing a U.S. climate observing system; supporting a new generation of coupled Earth System Models; strengthening research on adaptation, mitigation, and vulnerability; initiating a national assessment of the risks and costs of climate change impacts and options to respond; and coordinating federal efforts to provide climate information, tools, and forecasts routinely to decision makers.

In 2009, the NRC also published the report *Informing Decisions in a Changing Climate* (NRC 2009). This report examines the growing need for climate-related decision support, that is, organized efforts to produce, disseminate, and facilitate the use of data and information in order to improve the quality and efficacy of climate-related decisions.

In August of 2009, a group of prominent U.S. scientists concerned about climate change and the global carbon cycle wrote an article in the American Geophysical Union newsletter EOS, entitled *Carbon cycle observations: Gaps threaten climate mitigation strategies* (Birdsey et al., 2009). The article appealed for robust and sustained carbon cycle observations. They noted that "key elements of a national observational network are lacking or at risk" and strongly urged a coordinated system of observations that includes satellites, such as Landsat, MODIS, and SeaWiFS (as examples of key carbon-cycle tools vulnerable to loss), *in situ* observations, and direct atmospheric measurements to meet the needs of scientific understanding and mitigation policies.

Another U.S. Global Change Research Program report published in 2009, *Global Climate Change Impacts in the United States* (U.S.G.C.R.P. 2009), summarized the science and the impacts of climate change on the United States from 2009 and into the future. It was written to inform public and private decision making at all levels. It focuses on climate change impacts in different regions of the U.S. and on various aspects of society and the economy, such as energy, water, agriculture, and health. The report also highlights the choices we face in response to human-induced climate change.

In 2010, a suite of studies under an umbrella entitled *America's Climate Choices* was requested by Congress to examine the status of the nation's climate change research efforts and recommend steps to improve and expand current understanding (NRC, 2010a,b, c). The first report, *Advancing the Science of Climate Change* (NRC, 2010a), provides a compelling case that climate change is occurring and is caused largely by human activities, and that these conclusions are based on a strong, credible body of evidence. The second report, *Limiting the Magnitude of Future Climate Change* (NRC, 2010b), states that substantially reducing greenhouse gas emissions will require prompt and sustained efforts to promote major technological and behavioral changes. The third report, *Adapting to the Impacts of Climate Change* (NRC, 2010c), calls for a national adaptation strategy to support and coordinate decentralized efforts. Reducing vulnerabilities to impacts of climate change that the nation cannot, or does not, avoid is a highly desirable strategy to manage and minimize the risks.

Finally, in 2010, the NRC also published a report entitled *Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean* (NRC 2010d). This document reviews the recent legislation regarding ocean acidification, examines the current state of knowledge and identifies key gaps in information needed to help federal agencies develop a program to improve understanding and address the consequences of ocean acidification.

All of these many documents, as well as numerous meetings with the carbon cycle community, provided important guidance in developing this new Plan. The input highlighted the need for sustaining the activities outlined in the 1999 carbon cycle plan but also provided motivation for the new components of our plan we describe below.

2.4 Successes and remaining challenges

Research pursued under the guidance of the 1999 Science Plan has: 1) established a consensus that there is a large Northern Hemisphere terrestrial sink, but that we do not entirely understand where it is or the mechanisms controlling its variability, 2) recognized that the oceans are a major carbon sink, but the annual growth in the ocean sink is not able to keep up with the growth in annual CO_2 emissions, 3) acknowledged that we need to understand land use history in order to determine the present and future carbon budget, and 4) affirmed that we need to improve projections of the future behavior of the global carbon cycle.

Many of the research goals in the 1999 Science Plan remain important for the coming decade. New research thrusts are also needed, however, that we describe in more detail below. These thrusts include a need to evaluate uncertainties in the mechanisms controlling the carbon cycle, to understand the role of humans as agents and potential managers of change, to understand direct impacts of CO_2 on ecosystems, to better assess the uncertainties associated with elements of the carbon cycle, and to coordinate researchers from different scientific disciplines to address societal concerns. By sustaining research efforts from the last decade with new priorities for the next, we will make progress in the basic sciences and provide stronger scientific input to decision makers for carbon-cycle management decisions.

CHAPTER 3: Fundamental Science Questions

Research on the global carbon cycle needs to improve basic understanding of the human environment and to address the fundamental questions that confront public and private decision makers. Any new research agenda should be guided by the need to provide the science for making important decisions now, to anticipate the science needs for future decisions, and to address shortcomings in human understanding of our physical environment. As changes to the global carbon cycle continue to alter the atmospheric, terrestrial, and oceanic processes, carbon-cycle research needs to address the impact that humans are having on the environment and the effects that efforts to mitigate this impact will have now and in the future.

Given the background and history provided in Chapters 1 and 2, we define three overarching questions that guide the new U.S. Carbon Cycle Science Plan:

> **Question 1.** How do natural processes and human actions affect the carbon cycle on land, in the atmosphere, and in the oceans?
>
> **Question 2.** How do policy and management decisions affect the levels of the primary carbon-containing gases, carbon dioxide and methane, in the atmosphere?
>
> **Question 3.** How are ecosystems, species, and natural resources impacted by increasing greenhouse gas concentrations, the associated changes in climate, and by carbon management decisions?

3.1 Q1: How do natural processes and human actions affect the carbon cycle on land, in the atmosphere, and in the oceans?

This question supports an expansion of the process-oriented and diagnostic studies of air, land, and water that have been part of U.S. carbon cycle science for more than a decade. It also focuses increased attention on the effect of human actions on the carbon cycle, including new studies to address the socioeconomic processes controlling anthropogenic carbon emissions.

A process-level understanding of the carbon cycle is needed to understand and anticipate variability in CO_2 fluxes and atmospheric CO_2 concentration measurements and to develop credible projections of the future carbon cycle. Addressing these needs is critical for predicting future changes in climate as atmospheric concentrations of greenhouse gases are the primary driver of climate change. Significant progress has been made on developing global and regional carbon budgets over the last decade but many fundamental science questions remain. Furthermore, our understanding is insufficient for making accurate projections of the future carbon balance of the Earth. Particularly important for the coming decade are an improved understanding of thresholds and tipping points in the Earth's carbon cycle; increased studies of dynamic regions such as the tropics and boreal zones on land and the high latitudes and coastal regions in the oceans; and an improved understanding of the processes governing human impacts, such as disturbance of terrestrial ecosystems, on the Earth's carbon cycle.

The research needed to answer this question explicitly includes the role of humans in the Earth's carbon cycle. Direct emissions of carbon to the atmosphere from the burning of fossil fuels, land-use change, and disturbance are the dominant perturbations to the carbon cycle today and will continue to be so in the coming decades. The economic, political, cultural, ethical, and behavioral processes governing anthropogenic carbon emissions are an essential element of this U.S. Carbon Cycle Science Plan. This challenging research area is rich in fundamental science questions and critical to the management and policy decisions of the coming decades.

Along with its increased focus on the effects of human actions on the global carbon cycle, the first question highlights some additional research priorities. Our plan reinforces the need for enhanced natural-science research of the carbon cycle, but it also calls for a broadening of carbon-cycle research to include social scientists and other researchers who can address the human dimensions of the carbon cycle. Finally, it also proposes the development of integrated research programs where natural and social scientists collaborate on carbon-cycle research.

3.2 Q2: How do policy and management decisions affect the levels of the primary carbon-containing gases, carbon dioxide and methane, in the atmosphere?

This second overriding question seeks to understand how policy decisions and management choices - intentional or otherwise - alter atmospheric CO_2 and CH_4 concentrations, and, consequently, the Earth's climate and ecosystems. Examples of such decisions include the balance of renewable and fossil fuels for energy production, the use of land and ocean systems for carbon sequestration, and the production of biofuels. The rate and magnitude of changes in the carbon cycle today reflect dramatic, if sometimes unintentional, management choices made over the last two centuries. The impacts of increasing CO_2 and CH_4 emissions on Earth are substantial and, to reduce them, will require policy and management choices that are both scientifically, economically, and ethically sound, and politically and technically feasible.

Policy choices and carbon-management incentives should ideally reduce atmospheric concentrations of CO_2 and CH_4 while minimizing the risks of undesired side effects on the Earth's ecosystems, resources, and people. Effective decisions, however, are hampered by limited understanding of the impact of these decisions on people and the environment, the effectiveness at reducing greenhouse-gas concentrations, and the likelihood of side effects. Scientists need to provide a quantitative and credible understanding of the impact of different policy decisions and management choices.

3.3 Q3: How are ecosystems, species, and natural resources impacted by increasing greenhouse gas concentrations, the associated changes in climate, and by carbon management decisions?

Increasing atmospheric concentrations of CO_2 and CH_4 are fundamentally altering marine and terrestrial systems and could compromise the rich diversity and diverse services these ecosystems provide. The impacts of increased greenhouse-gas concentrations on ecosystems go well beyond changes in carbon storage, which is the focus of Question 1. For instance, increasing negative impacts on ocean biota and marine resources are anticipated in the coming decades as a result of rising CO_2 and ocean acidification (Doney, 2009). This concern about ocean acidification has emerged from fundamental research, and is now recognized as an important global carbon-cycle management issue. Increased atmospheric CO_2 concentrations in terrestrial ecosystems can alter the competitive balance among plant species through their stimulation of photosynthesis (Gill et al. 2002, Körner 2009). They can also contribute to large-scale changes in terrestrial ecosystem structure. On land and in the oceans, the direct impact of increasing atmospheric concentrations of CO_2 and CH_4 on species and ecosystems is a critical area for increased research.

It is difficult and probably ill-advised to decouple research on the direct effects of atmospheric CO_2 and CH_4 on ecosystems from the impacts of climate change caused by greenhouse gases on the same systems. Although research on the impacts of climate on ecosystems goes beyond the bounds of this Plan, we explicitly call for research that considers the combination of the factors in Question 3, given that ecosystems respond to the combined stresses of changes in climate and changes in atmospheric composition and also alter atmospheric composition and climate. Furthermore, many approaches for managing the carbon cycle, such as biological carbon sequestration, will have direct impacts on ecosystems.

Changes in the carbon cycle affect many ecosystem and natural-resource parameters. To fully address these questions, the carbon cycle science research community must be linked actively with the climate and ecosystems research communities. These connections will lead to a more holistic research program that considers a suite of environmental parameters, including: biodiversity and ecosystem health, water resources, disturbance, non-carbon greenhouse gases, resource economics, human health, and physical climate issues. Basic research on such environmental parameters is beyond the scope of a carbon-cycle plan. Nevertheless, new carbon-cycle research is vital to understand how ecosystems, species, and natural resources will be impacted by increasing greenhouse gas concentrations, climate change, and carbon management, and will in turn impact those factors reciprocally.

3.4 The critical role of observations

The field of carbon cycle science depends on well-designed, well-executed, and carefully maintained observations. Carbon cycle science cannot exist in the absence of these critical data. In support of all the research goals articulated in this plan, we need an optimally designed and integrated, long-term data collection and sustained observing system. A well-designed and maintained carbon cycle observing system will capture the atmospheric, oceanic, biologic, demographic, and socioeconomic data needed to establish baselines, evaluate change, understand processes, and evaluate mitigation activity (e.g., Houghton 2007). Data needs range from those of short-term experimental programs to commitments for long-term observations. These data are critical for tracking the global carbon system and providing a record of the variability in the major pools of carbon and their controlling processes. In addition, however, it is only through the availability of such sustained observations that we can evaluate models that attempt to diagnose carbon fluxes, attribute their variability to underlying processes, and predict their behavior as the climate system changes. Therefore, observations are central not only to providing a record of the past and current behavior of the carbon system, but also to predicting its future.

The 1999 U.S. Carbon Cycle Science Plan emphasized the establishment of atmospheric, terrestrial, and marine observational networks and experimental manipulations. These objectives of the 1999 Plan have been only partially achieved. Observational systems have been established and some networks have emerged, but the networks have not always been developed and maintained in a thoughtful, coordinated fashion; their long-term continuity has not always been ensured; the density of observations is highly irregular globally; and the types of observations collected are incomplete. The community has not focused, for example, on the continuity of observing systems or the observational needs outside of the physical sciences. Many manipulative experiments have been conducted but great uncertainty remains for the adequate number, type, location, and longevity of experiments that are needed to satisfy the science questions articulated in the 1999 Science Plan. In general, the U.S. research community has excelled at developing and testing innovative observational and experimental methods but has had more limited success transforming those observations and experiments that prove successful into sustained, long-term networks and facilities. The focus on innovation must be maintained and our ability to expand long-term observations and to maintain proven, essential data sources must be strengthened.

How to design effective experiments (where “experiment” here is meant in the broad sense of carbon cycle studies and observations, not strictly manipulative experiments) is a critical issue that must be addressed in the coming decade. The U.S. research community should focus more research on network and experimental design, with the design criteria emerging from a proper balance of basic science as well as carbon and climate management decision support needs (see Question 2 above). Further, the research community needs new financial models to support critical long-term observational and experimental elements. Although there has been some attempt to coordinate projects by agencies and through the national programs, a coherent, global-scale carbon cycle plan for sustained observations of critical variables cannot be accomplished effectively in 3-to-5 year funding increments. The model of short-term, single-investigator research projects is an excellent means of encouraging innovation but is not an effective way to maintain climate-scale observations that are essential for understanding the carbon cycle and for creating a global-scale carbon-cycle observing system. International collaborations in the design, coordination, funding, and maintenance of observational systems are another critical opportunity for enhancing carbon cycle science. Long-term networks and facilities, in addition, must not be static; network and experimental design research must be ongoing and our long-term observing and experimental systems must be periodically revised and updated to reflect new knowledge and needs.

A detailed listing of observational and experimental needs is beyond the scope of this chapter. However, Birdsey et al. (2009) have discussed many pressing observational issues facing the carbon-cycle science community today. For example, satellite observations of the land and oceans are a fundamental tool for carbon cycle research but the continuity and quality of these observations is threatened. Multiple means of observations and experiments from multiple U.S. agencies are essential, and both cross-agency and international cooperation and coordination will be critical to the success of carbon cycle science in the coming decade.

Data management and open data access must also be high priorities of a successful observing network in the coming decade. Unlike weather data, which tend to become less valuable with time, carbon and climate data tend to become more valuable. The archiving, management, documentation, and access to data in consistent, compatible, and easily accessible formats need to be carefully planned and thoughtfully implemented. Advances in data management and data analysis technology must be integrated into carbon cycle science. Data that are not available to the broad research community, or that do not include documentation sufficient to make these data interpretable, do not fully serve the global community. The U.S. research community must put the highest priority on open access to its data and must expect the same of international partners in this endeavor.

3.5 Dealing with uncertainty

In trying to balance the global carbon cycle and gain a process-level understanding of its components, it is important to evaluate, understand, and deal with the uncertainty that arises through measurements, models, analyses, and projections. As carbon cycle science moves into the public consciousness and stimulates political and economic decisions, knowledge of uncertainty is increasingly important to convey and address. Public opinion polls reveal confusion about the existence of anthropogenic climate change and a lack of common understanding. The complexity of the global carbon cycle dictates that few scientists will be expert in the full range of enquiries (e.g., Donner et al. 2009). This emphasizes the importance of clearly conveying what is known and the certainty attached to that information.

Dealing with uncertainty requires the tools to quantify the full uncertainty associated with observations and model estimates. Currently, uncertainties are sometimes reported in studies but these “uncertainties” really represent the sensitivity of the results to a small number of factors. In the coming decade, an emphasis needs to be placed on full uncertainty accounting so that the scientific community can express confidence that the correct value (whether it be an estimate of a carbon flux for a given region, the relationship between a climatic factor and ecosystem behavior, or any other aspect of the work outlined in the Plan) lies within the reported uncertainty bounds with an identifiable level of confidence. In many cases there is still a need to reduce uncertainty through targeted research, but in other cases it may be sufficient to simply be clear about the uncertainty of the information that we do have. We need to ask about the social utility of reducing uncertainty and the cost of doing so. Decision analysis requires good estimates of uncertainty and this is different than the desire to reduce uncertainty (e.g. Enting, 2008). Risk analysis involves both the likelihood and possible consequences of events. We need to improve predictive skill.

Characterization of uncertainty can be improved through additional observations or through modeling. In models there is both parameter uncertainty and uncertainty in model structure (i.e., the conceptual model), and inter-model comparisons can be useful in helping to understand uncertainty. As approached in recent IPCC publications, uncertainty can be conveyed as quantified measures expressed in probabilistic terms or as qualitative statements of the level of confidence based on the type, amount, quality and consistency of evidence.

It is beyond the scope of this document to define exactly how uncertainty should be quantified and clarified with the implementation of the Plan. There have been many documents published on the subject (e.g. Enting, 2008: Donner et al., 2009; Morgan et al., 2009). However, the U.S. community must work toward a more standardized approach for assessing uncertainty and improve its ability to clearly communicate these assessments to a broad audience as carbon cycle research becomes more accessible to policy makers and the general public.

CHAPTER 4: Science Plan Goals

The 1999 U.S. Carbon Cycle Science Plan (Sarmiento and Wofsy, 1999) provided a strong baseline from which the new Plan was developed. Many of the components of that initial plan remain important and need to continue. Given progress since the 1999 Science Plan and newer research challenges that have arisen, however, we propose several new directions for the coming decade. One area of emphasis is to devote more attention to human aspects of the carbon cycle, including the influences of social, political, and economic processes. Although human dimensions were mentioned in the 1999 Science Plan, the social and natural science components of carbon cycle research have not been well integrated. Another new component is to study the direct effects of increased CO_2 on ecosystems. The 1999 Science Plan focused primarily on carbon accounting. It did not adequately address issues, such as ocean acidification and restructuring of terrestrial ecosystems, which can have a dramatic impact on biodiversity and human food supply, independent of climate change. A third new direction is to expand the carbon science program to include research that is more responsive to decision support. In particular, scientists need to understand the effectiveness of potential carbon-management strategies (and inadvertent management strategies) to inform decision makers of the full consequences of such management. Recognizing that public policy and human actions are being motivated by concerns about global climate change, we also need to make a greater effort to understand and convey the uncertainty associated with our knowledge of the carbon cycle.

These new directions are reflected in the fundamental science questions described in the previous chapter. The science questions provide basic principles for guiding carbon cycle research but are unlikely to be answered completely in the next decade. To make progress in answering the questions and to provide guidance for human actions, we have outlined six science goals that should be addressed over the next decade, with proper funding and collaboration. These goals are listed here, together with references to the overriding questions they are primarily designed to address in parentheses:

Goal 1. Provide clear and timely explanation of past and current variations observed in atmospheric CO_2 and CH_4 - and the uncertainties surrounding them. (Q1, Q2)

Goal 2. Understand and quantify the socio-economic drivers of carbon emissions, and develop transparent methods to monitor and verify those emissions. (Q1, Q2)

Goal 3. Determine and evaluate the vulnerability of carbon stocks and flows to future climate change and human activities, emphasizing potential positive feedbacks to sources or sinks that make climate stabilization more critical or more difficult. (Q1, Q2, Q3)

Goal 4. Predict how ecosystems, biodiversity, and natural resources will change under different CO_2 and climate change scenarios. (Q3)

Goal 5. Determine the likelihood of success and the potential for unintended consequences of carbon-management pathways that might be undertaken to achieve a low carbon future. (Q1, Q2, Q3)

Goal 6. 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. (Q1, Q2, Q3)

One concern when dealing with a broad and multidisciplinary problem such as the global carbon cycle is the need to draw boundaries for the plan, especially because no research plan can address all facets of the problem. While the boundaries that we describe are not perfectly sharp, the motivation and scientific directions envisioned for each goal are further developed in the following sections.

4.1 Goal 1: Provide clear and timely explanation of past and current variations observed in atmospheric CO_2 and CH_4 - and the uncertainties surrounding them

Do we understand the processes behind observed changes in the atmospheric concentrations of CO_2 and CH_4? Are these concentrations changing in predictable ways in response to our mitigation initiatives? The scientific community needs to be able to provide to the broader public a clear and timely explanation of past and current variations observed in atmospheric CO_2 and CH_4, as well as the uncertainties surrounding these explanations. We note that "timely" is an important part of this goal; to serve public policy needs, atmospheric observations are needed in close to real time. To address this goal, we need to develop the capability to estimate variability in carbon sources and sinks as well as the processes controlling that variability.

4.1.1 Motivation

Understanding historical and contemporary variations in the carbon cycle is vital for science and society. Modern variability of trace gas distributions from the global observational network provides a direct record of anthropogenic influence on the chemical composition of the atmosphere, ocean, and biosphere, while also demonstrating the potential of natural phenomena such as El Niño and droughts to impact the current and future climate. Contemporary observational efforts, process studies (including experimental manipulations) and modeling are required for verifying surface flux estimates, including those of fossil fuel emissions, terrestrial biosphere uptake, biomass burning and land-use change and management, and the global ocean sink. Process-based understanding also makes it possible to predict future variations in the efficacy of natural terrestrial and oceanic carbon sinks. Where atmospheric increases are tied to human activities, it is important to understand the link between human activities and atmospheric concentrations and that purposeful management is having the expected outcome. Finally, sustained observations and modeling efforts provide an early warning capability for detecting possible changes, such as methane release from Arctic tundra or other unanticipated effects.

4.1.2 Progress over the last decade

Contemporary records of atmospheric and marine chemical composition have proven vital for verifying human impact on the Earth system. Of these, the steadily increasing concentration of CO_2 in the atmosphere revealed by the Mauna Loa Keeling curve is perhaps the most well-known and clearest evidence of anthropogenic change. Records such as these have been used to infer the importance of the land biosphere and the ocean in modulating atmospheric CO_2, including showing that the atmosphere has historically retained only about half of anthropogenic CO_2 inputs, that the ocean has switched from a net source of CO_2 in preindustrial times to a net sink absorbing 25-30% of the annual anthropogenic CO_2 emissions, and that the terrestrial biosphere of the northern extra-tropics currently represents a significant carbon sink. They have revealed the importance of the terrestrial biosphere in influencing atmospheric composition, and they have also similarly shown that large-scale climate modes (e.g. El Niño), volcanically-injected aerosols, and regional-scale precipitation and temperature anomalies can all leave detectable fingerprints on terrestrial carbon cycling. In the ocean, large-scale carbon surveys, time-series stations, and observations from instruments placed on commercial ships have shown that CO_2 concentrations in the surface ocean are increasing at about the same rate as in the atmosphere, but large scale circulation patterns are limiting the rate at which that CO_2 is moved into the ocean interior. Observed heterogeneity in the regional spatial pattern of rising ocean pCO_2, however, indicates changing physical and biogeochemical processes, suggesting that these changes may cause future ocean uptake of CO_2 to depart from its historical trend. Understanding the nature of these changes is critical for future development of ocean carbon-cycle models and thus for making accurate predictions of feedbacks that may alter the ocean's uptake of CO_2. Ocean observations have also demonstrated that ocean carbon uptake is strongly influenced by climate variability over a range of time scales as well as long-term trends in changing ocean chemistry.

4.1.3 Major uncertainties

Significant uncertainties remain about what processes cause the observed changes in the atmospheric and oceanic composition of CO_2 and CH_4. For instance, we cannot reliably quantify the relative importance of CO_2 fertilization and land-use changes for the terrestrial carbon sink in the northern hemisphere. Observations from repeat hydrographic surveys and process studies have revealed variability in the ocean interior that challenges our understanding of ocean circulation and biology. The connections between the land, ocean, and atmosphere in coastal zones are still poorly understood. Providing timely explanations of observed variations, with robust attribution to natural and anthropogenic causes, as well as communicating that understanding to decision makers and the general public, are thus important goals of the current plan.

4.1.4 Scientific directions

Establish a continuity plan and continue expansion of carbon observing networks

The ability to explain variations in atmospheric greenhouse gas concentrations is predicated on the ability to resolve the spatial and temporal gradients of the gases. Three- to five-year funding cycles typical of scientific investments are inadequate for capturing the long time scales and large spatial scales needed for observing trends in greenhouse gas dynamics. In order to achieve Goal 1 outlined above, the research community must establish an alternate model for supporting long-term observations.

In addition, current carbon observation networks have been unable to resolve competing processes and their net impact on atmospheric CO_2 and CH_4 concentrations. Filling this gap will require a systematic and coordinated expansion of global carbon observations. This expansion will inevitably involve *in situ* atmospheric concentration measurements, as well as an expanded array of greenhouse-gas observing capabilities from space. It should also involve additional *in situ* observations on land and in the ocean to better characterize the processes controlling carbon exchanges with the atmosphere and to help reconcile the differences between bottom-up and top-down flux estimates. Several of these efforts are already under way, including the continuing expansion of the NOAA ESRL Cooperative Air Sampling Network, the ongoing development of space-based missions such as OCO-2 and ASCENDS, the growth of the AmeriFlux network and NOAA’s ocean carbon observing network. To ensure that this expansion is both sustainable and optimal, however, the carbon cycle science community must establish unprecedented coordination, both internationally and domestically, among U.S.-based federal agencies in identifying the best set of activities aimed at ensuring sustained observations to answer key questions of carbon cycle science.

Conduct manipulative experiments to provide mechanistic understanding of responses and feedbacks to changing greenhouse gas concentrations and climate

Biologic systems are subjected to a variety of interacting stresses, and controlled experiments often provide the best way to identify how these stresses operate alone and together. For instance, experiments on the role of changes in atmospheric chemistry, temperature, precipitation, and pathogens on ecosystems provide the basis for modeling anticipated environmental changes.

Ongoing changes in the physical and chemical environment of the ocean are altering both the biological pump and the solubility pump in ways that can be described qualitatively but which cannot be coded in models because of insufficient understanding of the sensitivity of key processes to ongoing changes. These sensitivity factors must be constrained quantitatively before models can be used to make meaningful predictions of future ocean uptake of CO_2.

Ongoing changes in ocean stratification, winds, sources of micronutrients, acidification, supply of mineral ballast, land-ocean exchange, carbon and nutrient ratios of sinking organic matter etc., are all affecting ocean biogeochemical cycles and marine ecosystems. Perturbation of ecosystems, in turn, impacts the efficiency of the ocean's biological pump, both through altered nutrient utilization efficiency and in changes in the transmission of sinking organic material through the mesopelagic zone. These are critical uncertainties that must be examined through a combination of sustained observations and process studies.

Develop models capable of constraining process-based understanding of carbon flux variability

Whereas much effort over the past decade has focused on quantifying sources and sinks of CO_2 and CH_4 at increasingly fine spatial and temporal scales (i.e. diagnosing the variability in the carbon cycle), efforts at attributing this variability to underlying biogeochemical and socio-economic processes is still in its early stages. Therefore, an achievable result for the upcoming decade is to develop models capable of constraining the process-based understanding of observed variability.

Such improved models must not come at the expense of continuing efforts at quantifying the fluxes. Whereas the net global carbon flux can be quantified very precisely using even the current observational network, and while fluxes at sub-kilometer scales can be measured more directly, the discrepancy in reported fluxes at regional and smaller intermediate scales is still very large. These discrepancies include high uncertainty for issues as simple as separating the net oceanic and terrestrial fluxes, as well as disentangling biospheric from anthropogenic terrestrial fluxes.

4.1.5 Related Issues

This goal requires involvement of research on the human dimensions of the carbon cycle, because understanding the economic and policy effects on anthropogenic emissions and sequestration efforts is essential for understanding variations in atmospheric CO_2 and CH_4. In efforts to mitigate increases in atmospheric greenhouse gases, a process-based understanding is essential for how human activities impact greenhouse gas emissions and for verifying that atmospheric concentrations are in fact exhibiting the expected outcomes. Motivating human mitigation activities could be very difficult without a compelling attribution of consequences. In addition, achieving this goal will require close collaboration with many global observational efforts related to the carbon cycle. Measurements of trace-gas concentrations will remain crucial to verifying bottom-up estimates of fossil fuel emissions and land-use change, and may also be called upon to evaluate the efficiency of sequestration and other carbon management strategies.

To make the research developed in Question 1 accessible to public and private decision makers, carbon cycle scientists will need to develop more meaningful carbon system metrics that can be explained to the broader public and tracked through time. New advances in understanding will need to be captured from the scientific literature and made accessible to the broader climate change community. In this vein, we recommend and anticipate an increasing emphasis on integrating scientific understanding of the carbon cycle, as well as observations and model predictions, into integrated assessment models and other research tools used to evaluate and guide policy choices.

4.2 Goal 2: Understand and quantify the socio-economic drivers of carbon emissions, and develop transparent methods to monitor and verify those emissions. (Q1, Q2)

This goal seeks to derive process-level understanding of the human factors that determine carbon emissions from energy use, industrial activity, and land use. In particular, there is a strong need to characterize and understand the relative importance of key drivers of emissions regionally and over different temporal and spatial scales. It is equally important to improve our understanding of how policies may affect drivers. This improved understanding will enable better projections of future emissions from specific sources, including the implications of alternative policy scenarios. This research is timely not only as an essential component of understanding the evolution of the carbon cycle, but also as an input to current policy debates regarding the role of reducing emissions from deforestation and degradation (REDD), the implications of expanded use of agricultural lands for biofuels, and tradeoffs between carbon and other societal goals such as sustainable livelihoods.

As international and intra-national agreements to limit greenhouse gas emissions emerge, it is equally important to be able to independently measure, monitor and verify reported emissions. Inventories of greenhouse gas emissions have traditionally been self-reported by countries, communities, or companies based on survey data on the activities that generate emissions and coefficients that convert these to emissions estimates. With international commitments or economic drivers involved, methods and systems are needed for scientists from all countries to supply independent means for evaluating emissions and the impact of carbon management strategies. Atmosphere-based measurements, remotely-sensed observations, evaluation of socio-economic parameters, and other tools need to be developed to provide confirmation and confidence in mitigation commitments. This effort cannot be seen as the US checking up on the rest of the world so supporting international workshops and hosting visiting scientists from developing nations will be important ways to increase understanding and mutual respect in this area. The institutions and infrastructure for monitoring and verification must come from the international political process, but the tools and methods need to be developed by science.

4.2.1 Motivation

Human activity is now the dominant factor driving changes in the carbon cycle, and its impact is expected to grow throughout the 21st century. Understanding future changes in the carbon cycle must therefore include the study of the key drivers of emissions from human activity, whether from energy use, industry, or land use. Providing relevant information to policy makers on the carbon cycle must also include information on key human processes and drivers, as the effectiveness of many policies will depend on how human activities interact with these drivers. The effectiveness of policies will also depend on confidence that others are doing their agreed share. Although much can be done with self-reported emissions inventories and easily implemented improvements in those inventories, independent methods are sorely needed to improve and support self-reported estimates of emissions. One important role of the carbon-cycle science community is to develop tools, observations, and models that can be used to evaluate emissions, but, importantly, not necessarily to monitor and verify emissions directly in support of every carbon management policy.

4.2.2 Progress over the last decade

Research over the past decade have led to significant advances in understanding factors affecting anthropogenic carbon emissions, including the role of land use-change, changes in consumption patterns, and urban development. A growing number of economic and technological analyses of carbon management and conservation strategies have also been aimed at limiting anthropogenic emissions. These efforts have been conducted by various research communities, including those who study land use and cover change (i.e., LUCC and Global Land Projects), urban form and metabolism (i.e., Urban and Global Environmental Change (UGEC)), technological development, energy resources, and integrated assessment modeling. There has also been an emerging body of work on cities, behavior change, and willingness to pay for carbon offsets or to change various types of behavior in response to climate change. While much of this work has taken place outside the carbon-cycle science community as traditionally defined, tremendous opportunity exists to link to, and enlarge, the scope of research on drivers affecting emissions and carbon uptake.

Through efforts of the Intergovernmental Panel on Climate Change and other groups, marked improvement have been seen over the last 15 years in standardized methods and implementation for greenhouse gas emissions inventories. Current best practice in developed countries is able to produce reasonably accurate estimates of emissions (NRC, 2010a) of CO_2, and yet there is little data that is internationally independent and transparent for extending the inventories to all countries and supporting confidence in mitigation agreements. Land and space based approaches to support inventories or to falsify some inventory components need to be explored, and evaluation and modeling of related demographic and economic data are needed.

4.2.3 Major uncertainties

Though we have greatly improved our basic understanding of socio-economic drivers of anthropogenic emissions and carbon use, many uncertainties remain. For example, there is still significant uncertainty in current emissions, particularly from land use and for anthropogenic emissions regionally. Likewise, uncertainty in how emissions may evolve over the next few decades has received little attention, despite the fact that, given the long lifetime of carbon in the atmosphere, short- to medium-term emissions trends have significant consequences for atmospheric concentrations later in the century. In terms of a process-level understanding of drivers, advances have been made in particular sectors, such as energy analysis, land use change studies, urban footprint analysis, and international trade. A high priority now is to understand interactions among those drivers. An integrated systems understanding of the interactions among socio-economic, policy, and cultural factors at different spatial and temporal scales will allow development of more effective mitigation and adaptation strategies. In addition, how socio-economic drivers of emissions and uptake interact with biophysical components of the carbon cycle is only beginning to be explored. As a prominent example, a substantial amount of research effort in the carbon-cycle and climate communities will be based on Representative Concentration Pathways (RCPs) developed for use in the IPCC assessment process. Development of socio-economic scenarios, including emissions drivers and their interactions, is at an early stage and will require substantial new research.

Explorations with inverse modeling and preliminary studies of airborne and satellite measurements are beginning to establish relationships between CO_2 fluxes and observations of atmospheric concentration. We do not know with certainty what kind of surface-measurement system and modeling will be required for useful estimates on the emissions of cities, countries, or regions.

4.2.4 Scientific directions

In defining key scientific directions in the study of the drivers of anthropogenic carbon emissions and influences on sinks, we draw on a typology that distinguishes direct from indirect drivers (Millennium Ecosystem Assessment 2003). A driver is any natural or human-induced factor that directly or indirectly causes a change in anthropogenic emissions or alters carbon sinks. Direct drivers unequivocally influence emissions or sinks and therefore can usually be unambiguously identified and measured; indirect drivers operate more diffusely and typically affect emissions or sinks through their effects on direct drivers.

For example, direct drivers of emissions and influences on sinks include:

- The combustion of fossil fuels
- Industrial processes, such as the production of cement that generates greenhouse gases and some waste management processes
- Land use change that modifies terrestrial carbon sinks
- The purposeful sequestration of CO_2 in plants, soils, the ocean, or geologic reservoirs
- Processes leading to the emission of nitrogen gases and ozone precursors (which can affect the size and sign of terrestrial sinks)

Indirect drivers include a wide range of human activities that influence direct drivers and therefore lead to changes in emissions or the operation of sinks, including the following key categories:

- Demography (population growth/decline, urbanization, aging, living arrangements)
- Economics (economic growth, wealth distribution across countries/sectors/individuals, trade, and incentives)
- Science and technology (research and development, technology diffusion, and their implications for energy supply, end use efficiency, agricultural productivity, sequestration methods)
- Legacy effects of land use, such as the time since deforestation or agricultural abandonment, which influence carbon uptake today
- Behavior (lifestyles, culture)
- Institutions (changes in markets, regulatory regimes, property rights)

Furthermore, changes in policy, conditioned by indirect drivers, will have a critical influence on direct drivers and therefore on emissions and sinks. For example, policies that place a value on carbon, promote technology development, or use incentives to change behavior, can have a strong influence on fossil fuel combustions, land use change, and other direct drivers influencing the carbon cycle.

Scientific progress on understanding how human activities influence the carbon cycle, and how these effects might evolve in the future, requires achieving the following objectives.

Quantify the relative importance of different socio-economic processes and their interactions in different parts of the world and at different spatial and temporal scales.

Anticipating future carbon emissions and uptake requires understanding which processes are the key drivers in different places and over diverse timescales. Socio-economic conditions and trends vary widely in different parts of the world. For example, demographic trends vary within and across nations, with some populations growing while others decline, and some areas urbanizing more rapidly (Cohen, 2003). Economic growth is proceeding at different rates and levels of energy- and carbon-intensity. Land use patterns also vary widely with different factors such as agriculture, forestry, international trade, and demographics playing various roles in different places (Lambin et al., 2001).

Influences on the carbon cycle are driven not by single socio-economic factors but by combinations of factors acting together. Understanding interactions among drivers is therefore crucial for anticipating future emissions. For example, we need research to understand relationships between economic development and demographics; linkages among economic growth, technological change, globalization, and energy systems; and how different types of policies will influence land-use emissions. Finally, the relative importance of drivers will differ across spatial and temporal scales. The drivers of emissions at the level of an individual city, for example, can differ substantially from those driving emissions nationally, regionally, or globally. In addition, some processes, such as fluctuations in economic growth rates, may be important over a few years, other processes such as urbanization can be important over several decades, and still others, such as changes in energy supply technologies, are important over many decades to a century.

Better quantify the potential range of future emissions from energy and land use

Improving our ability to anticipate the possible future evolution of the carbon cycle will require improved projections of emissions and of human influences on carbon uptake. However the ultimate goal of such projections is typically not to predict future conditions precisely, since many uncertainties in complex socio-economic systems are irreducible, particularly over long time horizons (Taleb, 2007). Rather, the key goal is to better quantify the uncertainty in projections. In particular, an improved understanding of the plausible range of future emissions, land use, and disturbance, and influence on sinks, will be critically important for informing policy and research related to the carbon cycle. Whether short-term fluctuations in emissions portend longer-term trends in emissions growth remains an open question (Raupach et al., 2007), and even estimates of current emissions from land use are highly uncertain. How rapidly the effect of human activity on the carbon cycle will grow, and how rapidly it may be curtailed, are critical questions that also require concerted interdisciplinary research. The necessary work will include drawing on new studies of emissions drivers, improved data on current and past socio-economic conditions and trends, and improved models of the interactions of socio-economic processes driving emissions and land use.

Determine how carbon prices and other policies affect socio-economic drivers and emissions

With increasing attention to developing and implementing policies that mitigate human influence on the carbon cycle, the importance of understanding how policies, particularly those that place an economic value on carbon, will affect the processes driving emissions is increasingly important. How will different policies influence the pace and direction of technological change, patterns of land use, and the consumption choices of individuals? How are changes in indirect drivers likely to influence policy decisions? How might alternative potential policy goals, including concentration or temperature stabilization goals, influence the types and timing of policies to be implemented? Progress on this goal will require concerted efforts to study the economics of carbon, and interdisciplinary research linking economics, energy systems analysis, land use science, and models of the natural carbon cycle.

Develop the tools, observations, and models needed to quantify and evaluate emissions

Efforts to limit emissions will depend on being able to motivate and measure the success of those efforts and to instill confidence that objectives and commitments are being met. Gas concentrations, isotope signatures, trace species, land surface properties, and measures of socioeconomic drivers all provide data potentially useful for monitoring and verification. Many of these observations are best obtained through a combination of *in situ* and remote-sensing observations of atmospheric constituents and Earth surface properties necessary for assessing carbon stocks and flows. Models need to be developed to accurately constrain emissions based on the information provided by these various types of measurements.

Systems that are appropriate for cooperative parties or countries and those that might be used for uncooperative parties need to be considered. International partnerships and collaborations will play a central role in establishing measurement systems and analyses that provide reliable and transparent results. The carbon cycle science community is in a unique position to develop the tools, observations, and models needed to quantify and evaluate emissions. These tools can then be used in support of carbon management policies. It is important to distinguish, however, the role of the carbon cycle science community in the scientific development of these tools, and the role of decision and policy makers in monitoring and verifying emissions and compliance with carbon management strategies.

4.2.5 Related Issues

A large body of research is underway on several aspects of the drivers of emissions and influences on uptake, including work by research communities in integrated assessment modeling (e.g. US DOE, 2007), urbanization (e.g. UGEC, 2010), energy systems (e.g. The Global Energy Assessment (IIASA, 2010)), the Global Land Project (GLP, 2010)), and the Global Carbon Project (GCP, 2010). However, this work is not currently being carried out in a coordinated fashion that recognizes and treats socio-economic processes as an integral component of the broader carbon cycle. Future research would greatly increase its chances for significant progress in understanding by better coordination across these communities.

4.3 Goal 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 more difficult.

All carbon reservoirs and carbon processes are not equally vulnerable to change, resilient to stress, responsive to management, or susceptible to unintended consequences of management decisions. We need to be able to identify which carbon pools and flows are most vulnerable and to understand the physical, chemical and biological processes important in determining the degree of vulnerability of these pools and flows. We also need to predict the consequences of carbon management and sequestration schemes on vulnerable pools and to support carbon management goals by prioritizing the most vulnerable stocks and flows and the resources that are needed to assure the stability of these.

Vulnerability also needs to be understood in terms of direct feedbacks to the climate system because, for example, changes in the physical and chemical characteristics of the oceans can impact the distribution of heat and moisture in the Earth system and changes in terrestrial carbon stocks can affect the land surface energy balance through changes in albedo and latent heat transfer.

4.3.1 Motivation

The carbon cycle will respond to climate change in major ways, but not all carbon reservoirs and carbon processes are equally vulnerable or resilient to stress. Vulnerable carbon pools may release a large amount of carbon, providing a positive feedback to climate change. Some changes may also be abrupt or not easily reversible. Identifying vulnerable carbon stocks and flows, understanding the processes controlling their behavior, and evaluating the risk and magnitude of significant changes to their net impact on the carbon cycle is critically important in anticipating the degree of future climate change. We need to improve our skill and confidence in anticipating hot spots and tipping points of the most vulnerable future changes. Predicting the likelihood of substantial changes in vulnerable carbon stocks and flow is necessary for devising strategies for climate mitigation, adaptation and carbon stock management. By far the largest "active" pools of carbon on Earth are in the ocean and soils. Even if these pools are not currently considered the most vulnerable, it is important to continue to assess the processes controlling exchanges with these pools as even a small change in the net balance of exchanges could have a significant impact over time.

4.3.2 Progress over the last decade

Important progress has been made in identifying some vulnerable carbon pools in recent years, including carbon sequestered in high-latitude permafrost, carbon sequestered in peatlands in tropical and other regions, carbon stocks in forests vulnerable to insect pests or wild fires, carbon stored in soils vulnerable to plowing and decomposition, carbon stored as methane clathrates on land and in the ocean, and carbon stored in ocean basins that are vulnerable to changes in biology or ocean circulation. Recent estimates have suggested that very large stores of carbon exist in some of these vulnerable pools, such as permafrost (Schuur et al. 2008). In the case of permafrost, large quantities of methane could be released if substantial amounts of permafrost melt as bacteria feed on the ancient carbon and nutrient stores at high latitudes (Walter et al., 2006). These stores are not well represented in existing models, and theoretical and modeling studies have suggested a range of possible ecosystem shifts in response to global warming (Schneider et al., 2007). For instance, vulnerable carbon reservoirs exist in areas such as tropical rainforests, due to the potential of future drought in the subtropics (Cox et al., 2000), or tropical peatlands, through draining for land-use change and subsequent carbon loss from fires after drought (Page et al. 2002). Coupled carbon-climate models suggest potentially large climate feedbacks due to changes in these vulnerable carbon reservoirs, leading directly to accelerated warming.

The ocean contains more 50 times more carbon than the atmosphere does and will ultimately, over millennia, absorb most of the fossil carbon released to the atmosphere. Estimates of the current uptake have greatly improved over the last decade. Although the oceans are not currently considered the most vulnerable carbon pool over decadal time scales, additional understanding of how future ocean uptake may change is still needed. However, rapid changes are occurring in some marine systems, such as carbon storage and fluxes in coastal wetlands and waters (e.g. Cai 2011), coastal hypoxic zones, and the high latitude ocean margins and basins (e.g. Bates et al., 2009).

4.3.3 Major uncertainties

Uncertainties associated with changes to vulnerable carbon stocks and flows are still large (Schimel et al. 2001, Friedlingstein et al., 2006). Given that approximately half of the carbon released through fossil fuel burning is currently taken up by sinks on land and in the ocean, predicting the future carbon balance of these major reservoirs is critically important. There are major gaps in our understanding of how the carbon cycle responds to climate change. Important processes are affected differently by changes occurring over diverse time scales, such as short-term climate disturbance versus long-term climate change. Additionally, human activities and land management can change rapidly through economic incentives or global trade. Biofuels are an example of how quickly grasslands, croplands, and other ecosystems can be converted based on policy or economic incentives.

An additional uncertainty is that all vulnerable carbon reservoirs and flows have not been identified or thoroughly assessed. The processes that control the ways in which these carbon reservoirs on land respond to changes in temperature, soil moisture and other factors or in the oceans to changes in carbonate chemistry or the health of marine phytoplankton and surface mixing are generally not well known. Even for vulnerable stocks that are well known, significant uncertainties remain. For example, permafrost carbon pools under tundra and on the continental shelves are ancient, and gaps in our understanding remain for how they were formed and evolved under past changing climate and possibly human influence. One major challenge is the balance of competing effects and feedbacks that cannot be assessed without a holistic view. For instance, the potential loss of soil carbon at high latitudes may be countered by increased vegetation growth, and the net carbon loss or gain may be sensitive to the degree of warming (Qian et al., 2010).

4.3.4 Scientific directions

Several key research directions have been identified for improving our understanding and for predicting changes in vulnerable carbon stocks and flows. These key directions include identifying the vulnerable pools and flows as well as studying and modeling the processes that make them vulnerable and the potential consequences of this vulnerability.

Identify vulnerable pools and flows and monitor their changes, especially those that may change more rapidly in the near future.

Some carbon reservoirs and carbon processes are more vulnerable to changes in climate or carbon cycling than others. Moreover, carbon reservoirs and processes differ in their resilience to stress, responsiveness to management, and susceptibility to unintended consequences of management decisions. Research needs to focus on quantifying the known vulnerable pools and flows, tracking changes in their size and rates of change, and identifying and evaluating any other vulnerable pools or flows. Long-term, sustained observational networks must include *in situ* and remote-sensing observations as well as examinations of historical records.

Understand the physical, chemical, and biological processes important in determining the degree of vulnerability of carbon pools and flows, and build such understanding into diagnostic and mechanistic models.

To anticipate future changes, and to plan for management actions, we need a thorough understanding of the processes underlying potential changes in vulnerable carbon pools and flows. Controlled experiments can play an important role in this effort because parameters can be manipulated to represent possible future carbon and climate scenarios, so that vulnerability under extreme conditions and novel combinations of environmental factors can be tested. Diagnostic and mechanistic models then become critical in delineating and quantifying the relative roles of the processes controlling carbon balance in vulnerable reservoirs. The many processes involved in the carbon cycle demand collaboration and knowledge from an unprecedented number of traditional fields, and pose a major challenge in the management of scientific research. We must develop effective new ways to facilitate interdisciplinary and innovative research to address this need. The links to physical oceanography and surface land energy balances need particular attention.

Predict the likelihood, timing and extent of potential changes in vulnerable carbon stocks and flows with numerical models and empirical methods.

Empirical methods are valuable for extending our knowledge of past changes into the future. Numerical models represent the biological, physical, and chemical processes controlling carbon balance and can be informed by available observations; they provide a key tool for predicting future changes in a mechanistic way. Therefore, we need to develop models to represent accurately the past, present, and future behavior of vulnerable carbon stocks and flows. Model inter-comparisons offer a useful opportunity to integrate knowledge across modeling platforms. This approach is especially important as vulnerability is often non-linear, and abrupt changes may not be easily constrained by past short-term observations.

Predict the consequences of carbon management and sequestration schemes on vulnerable pools; support carbon management goals by helping to prioritize the most vulnerable stocks and flows that require management and the resources that are needed.

Comprehensive models will also be an essential tool in evaluating carbon management schemes, in order to avoid unintended consequences of proposed management strategies. Such consequences may be difficult to anticipate due to the complexity of the carbon cycle, and carbon cycle models offer a tool for balanced evaluation. An exciting opportunity in using carbon cycle models is to identify the most vulnerable carbon stocks and flows. Once those vulnerabilities are clearer, we can test management possibilities and evaluate effectiveness in reducing vulnerability and altering the global carbon budget, including the resources needed for achieving these management goals.

4.3.5 Related Issues

Vulnerability in terrestrial carbon pools and fluxes is directly related to physical changes in ecosystems and climate, including changes in water resources, energy, food supply, resource extraction, and livelihoods. Because abrupt changes in vulnerable carbon pools may be eye-catching, links to the public, media, and decision makers may be direct and prompt. On the other hand, vulnerability in marine systems may be more related to water, carbon, and energy flows and will be manifest in quite different ways. Public perceptions and management decisions need to be informed by process-based understanding and clear understanding and presentation of uncertainty.

4.4 Goal 4: Predict how ecosystems, biodiversity, and natural resources will change under different CO_2 and climate change scenarios.

Increasing concentrations of atmospheric carbon dioxide and other greenhouse gases have been and will continue to be a reality for the foreseeable future. The direct effects of elevated greenhouse gas levels, along with the accompanying changes in climate, are likely to alter ecosystems profoundly on land and in marine and freshwater environments. The interaction of climate change and the carbon cycle is of primary importance, and this interaction is discussed in goals 1, 2 and 3, recognizing that the ecosystem effects of climate change go far beyond the scope of the Carbon Cycle Science Plan. The specific focus of the goal presented here, therefore, is to focus on the *direct* impact of increasing atmospheric greenhouse gas concentrations on ecosystems, beyond their potential role as carbon reservoirs or sinks. Three examples of such impacts are altered marine ecosystem structure due to ocean acidification, biodiversity impacts on land, and the potential stimulation of additional CO_2 on net primary productivity.

4.4.1 Motivation

Atmospheric levels of carbon dioxide and other greenhouse gases are strongly mediated by terrestrial and aquatic ecosystem processes. Correspondingly, ecosystems are highly sensitive to changes in greenhouse gas levels, even in the absence of climate change. For instance, rising levels of atmospheric CO_2 and other greenhouse gases alter many ecological factors, such as the chemistry of surface waters and the biodiversity of terrestrial and marine ecosystems. These and other effects have critical implications for society, including impacts on fisheries and agricultural production. Moreover, understanding these effects is critical to identifying potential feedbacks and thresholds in the interactions among ecosystems, climate, and atmospheric chemistry.

4.4.2 Progress over the last decade

Over the past decade, we have come to a better understanding of the profound ecosystem changes that have occurred with changing greenhouse gas concentrations and other climate-related forcings. Shifts in ecosystems due to changes in temperature, water availability, increased carbon dioxide levels, and other factors have altered biodiverwity, ecosystem structure, and associated partitioning of carbon between land or ocean and the atmosphere (Denman et al., 2007, Field et al. 2007). In terrestrial systems, the range and phenology of many species are already changing in response to climate change (Root et al., 2004; Rosenzweig et al., 2008). In many parts of the world, future species composition is expected to differ substantially from today (Williams et al., 2007).

In coastal and marine ecosystems, rising sea level and intense coastal development have led to widespread loss of vegetated coastal habitats including mangroves, salt marshes, and seagrasses, negatively impacting carbon burial capacity and biodiversity (Duarte et al., 2005; Waycott et al., 2009). Alteration of seawater chemistry from excess CO_2 has been well documented, and the resultant ocean acidification threatens coral reef ecosystems and other benthic and pelagic marine food webs, and could diminish both biodiversity and the effectiveness of ocean carbon sinks (e.g., Riebesell, 2008). Some satellite observations suggest long term declines in global ocean productivity related to climate (Behrenfeld et al., 2006) and an expansion of oligotrophic ocean waters presumably related to increasing ocean thermal stratification (Pörtner, 2008). A further consequence of the combined effects of rising CO_2 and ocean warming is an expansion of ocean dead zones (Brewer and Peltzer, 2009).

4.4.3 Major uncertainties

Major uncertainties remain in our understanding of how marine and terrestrial ecosystems respond to increasing greenhouse-gas concentrations. Recent findings that ecosystem structure can substantially alter vertical export of carbon in ocean ecosystems (Buesseler et al., 2007) are not accounted for in current global models. Furthermore, changing ocean stratification and thermohaline circulation, reduced extent of sea ice, and altered cloud-forming sulfate aerosols can profoundly influence ecosystem structure and function. Ocean acidification represents an emerging threat to the health of ocean ecosystems and its effects have only begun to be examined. Non-linear feedbacks and thresholds are critical to understanding the complex responses of ecosystems and their future role in the carbon cycle.

Considerable uncertainties remain for terrestrial ecosystems. One example is how extensive future plant growth, through enhancement of photosynthesis, will be with additional CO_2. If plants and the soil fail to take up as much carbon as is currently represented in global models, then hundreds of gigatons of additional CO_2 will remain in the Earth's atmosphere, making the job of atmospheric stabilization even more difficult than currently assumed. A second uncertainty is how the frequency and extent of regional disturbances will change in the future. A southwestern United States that is warmer and drier is almost certain to experience increased fire frequency and severity. A third uncertainty is the extent to which greater atmospheric CO_2 concentrations may change the competitive advantage of different species and change overall diversity.

More extensive study and enhanced measurements of marine and terrestrial ecosystem changes should be a key element of a comprehensive carbon cycle science strategy. Moreover, because sustaining healthy and diverse ecosystems is an important means of reducing greenhouse emissions in the face of changing climatic conditions (Turner et al., 2009), carbon cycle science must address strategies for preserving critical ecosystems and associated biodiversity.

4.4.4 Scientific directions

A scientific approach to address ecosystem impacts must involve a two-tiered effort that would 1) reduce uncertainties in understanding of, and ability to predict, ecosystem responses to changes in greenhouse gas levels and, 2) sustain and enhance capabilities to observe changes in ecosystems as they occur. These general goals are addressed in more detail below.

Improve understanding of, and ability to predict, responses of ecosystem productivity, biodiversity, and sustainability to changing levels of carbon dioxide and other greenhouse gases.

Efforts to reduce uncertainties in our understanding of ecosystem impacts will require improved models supported by *in situ* and remote-sensing observations, as well as experimental manipulations and process studies that address changes in ecosystem productivity, biodiversity, and susceptibility to changing levels of carbon dioxide and other greenhouse gases. Studies should examine the effects of rising CO_2 as well as other greenhouse gases on terrestrial ecosystems and possible responses in productivity and community composition. Additional work should examine ocean ecosystem responses to rising CO_2 and other gases, and their associated consequences. These efforts should also include work to examine ecosystem consequences of carbon sequestration strategies.

Determine the synergistic effects of rising CO_2 on ecosystems in the presence of altered patterns of climate and associated changes in weather, hydrology, sea level, and ocean circulation.

Additional efforts will be needed to determine effects of altered patterns of climate on ecosystem structure and function in terrestrial and marine habitats. Although this broad topic extends well beyond the scope of this Plan, aspects of this question fit well within the Plan's purview. Linkages between land and ocean ecosystems represent an issue that is particularly sensitive to change and has important significance both for species and for society. These linkages are also only beginning to be examined in the context of carbon export to the coastal oceans, and the impact of this export on coastal ocean acidification. Disproportionately large changes are also anticipated for arctic ecosystems; consequently, a comprehensive science plan should include efforts to characterize ecosystem impacts in these regions, and the ways in which they feed back to the carbon cycle. Interactions between human society and ecosystems must also be addressed, as human activities have the potential to profoundly alter ecosystems on land and in the water. Of particular importance are ecological and climatic changes in the tropics where food production and vulnerability to climate change are key concerns.

Enhance capabilities for sustained and integrated observations of ecosystems in support of scientific research as well as management and decision-making.

Although targeted science goals to reduce uncertainties is important, immediate action is needed to develop our capabilities to observe ecosystems and provide critical information for scientific research as well as for environmental managers and decision makers. A comprehensive and integrated system of observations is essential for providing a baseline of existing conditions and the critical information needed to track and manage future change. Monitoring terrestrial and marine ecosystems is also a key component necessary for validating and refining models and identifying non-linear responses and feedbacks.

Observational infrastructure should include terrestrial and ocean observation platforms, as well as remote-sensing observations, to provide time-series of environmental conditions and ecosystem properties. Remote-sensing capabilities must be maintained and enhanced to enable larger scale tracking of changes in critical ecosystems. Additional technologies, including airborne sensors, unmanned aeronautical vehicles, long-term field stations, moorings, floats and underwater vehicles, can be used to further expand observational capabilities. These efforts should be integrated where possible with process studies to examine *in situ* responses to changing greenhouse gas concentrations and climatic forcing.

4.4.5 Related Issues

Because ecosystems play a fundamental role in mediating atmospheric levels of greenhouse gases, this goal is related to numerous other aspects of this Plan and to many aspects of ecology generally. Furthermore, an understanding of ecosystem dynamics is needed to develop accurate predictions of future changes and potential feedbacks and non-linear responses. Finally, the impacts of increasing greenhouse gases on ecosystem structure and function are inextricably linked both to the capacity of these systems to sequester carbon, and to impacts with other elements of climate change, including links to hydrology, land use change, and sea level rise. Whereas impact on carbon fluxes and storage are covered in other goals of this Plan, the broader set of feedbacks with climate change extend well beyond the scope of this Plan. Clear collaborations with, and linkages to, other scientific areas within the purview of the U.S. Global Change Research Program must be reinforced to coordinate research in this critical area.

4.5 Goal 5: Determine the likelihood of success and the potential for unintended consequences of carbon-management pathways that might be undertaken to achieve a low carbon future.

As concerns increase over anthropogenic impacts on atmospheric concentrations of greenhouse gases their impacts on the global carbon cycle, it is critically important to determine the likelihood of success and the potential for unintended consequences of possible carbon-management pathways to achieve a low carbon future. This goal aims to understand interlinked natural and managed systems sufficiently for individuals, corporations, and governments to make rational and well-informed decisions on how best to manage the global carbon cycle, and especially the anthropogenic impacts on this cycle.

4.5.1 Motivation

The global carbon cycle is complex and closely linked to the energy, water, and nutrient cycles on Earth and to demographic and economic systems globally. Efforts to manage the carbon cycle will have broad environmental and economic impacts. Ethical and equity issues are central to what actions might be taken, who takes them, and what consequences result. The myriad of interconnected factors affected by carbon management strategies must be understood and taken into account to determine the likelihood of success of alternative carbon management schemes.

In addition, low carbon strategies have the potential to harm local and distant ecosystems and communities. Issues characterized as “food vs. fuel” or “indirect land-use change” represent the emerging edge of concern about the impacts of carbon mitigation strategies. Those systems that utilize large land areas will potentially displace small landholders and sharecroppers through land consolidation to produce biomass or to harvest solar or wind energy; they will similarly impact the Earth surface energy balance, biodiversity, and water balance. Proposals to inject carbon dioxide into the deep ocean have been diverted by concerns about effects on marine ecosystems, and carbon sequestration in the biosphere has raised questions about changes in albedo. All of these interconnections among environmental and economic concerns require that we have a clear understanding of the impacts of alternatives, both the aggregate impacts on the global system and the distribution of these impacts regionally and locally.

4.5.2 Progress over the last decade

Considerable progress has been made over the last decade in determining the net greenhouse gas balance of some carbon-mitigation activities. For instance, corn-ethanol production has been shown to have a less positive carbon balance than originally expected by some scientists and policy makers (e.g., Fargione et al. 2008, Searchinger et al. 2008, Piñeiro et al. 2009). As such, the climate benefits of the 2007 Energy Independence and Security Act mandating the use of 36 billion gallons of biofuel by year 2022 have been questioned. Clear estimates of carbon savings along with the potential consequences of carbon-sequestration strategies for other greenhouse gases, such as methane and nitrous oxide, water and other ecosystem services are urgently needed (e.g., Jackson et al. 2005). Many potential decisions have both positive and negative consequences, and scientists need to provide a comprehensive, quantitative analysis of the trade-offs of greenhouse gas emissions, other environmental impacts, economic and social impacts, and the distribution of costs and benefits.

4.5.3 Major uncertainties

Low carbon futures will impact both environmental and economic systems, and we are just beginning to understand the range and magnitude of the issues. Questions as apparently simple as the trade-offs between the capital investment in a new car and the savings that will be achieved during operation are important to confront, in both environmental and economic terms. As low carbon strategies are implemented, both the environmental and social impacts will be felt in different places and sectors of the communities undertaking the effort - changes in energy availability and cost; access to various resources such as land, water, and food production; and livelihoods will be apparent. Not all segments of society will equally share in the profits and the burden in the shift of employment, economic gains, and environmental improvements, and these differential costs and benefits are poorly understood. In many cases we cannot accurately characterize the aggregate costs and benefits, let alone the distribution of those costs and benefits. For low-carbon strategies that achieve aggregate climate and other environmental benefits, institutional structures will be needed to motivate adoption and to provide oversight in the sharing of gains and losses as deployment of the low carbon strategies are carried out. Additional research is needed into what institutional structures will be most effective in providing motivation, oversight and verification of carbon management goals.

4.5.4 Scientific directions

As society moves into a phase of active carbon management, several research issues need to be addressed to determine the efficacy of proposed strategies.

Develop mechanisms for evaluating, integrating and balancing interconnected and potentially competing management goals within the context of carbon cycle science

Continuing the biofuels example from above, in the development of a low carbon strategy, there are many considerations associated with societal goals. These considerations include climate protection, food security, human-well being, conservation of biodiversity, and maintenance of ecosystem services of land and ocean domains. Recent concerns have been raised for the potential impacts of bioenergy on socio-environmental dimensions that would compromise these goals, including enhanced greenhouse gas emissions and increased nitrogen pollution that could undermine some of the benefits associated with bioenergy. A critical initial step is to ensure that strategies to reduce greenhouse gas emissions do indeed reduce greenhouse gas emissions. Whether these are technical strategies like development of cellulosic ethanol or social strategies like promotion of mass transit, detailed systems analyses are needed to ensure that the greenhouse gas benefits are real. The challenge in devising any low carbon development strategy is to collectively achieve multiple goals while recognizing the trade-offs across the suite of benefits and liabilities that comprise the decision process. Research is needed to identify mechanisms that minimize the net negative effects across a spectrum of goals. A more integrated approach to evaluating the impact of these low energy strategies is also needed to better understand the impact these strategies have on the environment and on socio-economic factors.

Determine the impacts of carbon management and sequestration strategies on sustainability of ecosystems and ecosystem services, including water resources and biodiversity.

Sustaining healthy and diverse ecosystems is an important means of reducing greenhouse emissions and maintaining ecosystem resiliency in the face of the changing carbon cycle and climate (Turner et al., 2009). Carbon-cycle science must address current uncertainties about land and marine management opportunities to sequester carbon while preserving biodiversity, water resources, and other critical ecosystem functions. Research is also needed to address the societal benefits of healthy ecosystems as well as approaches to adjusting societal behavior to promote ecosystem sustainability.

Quantify the net climate effects of carbon-management pathways, including albedo and other energy-balance components that influence temperature.

Policies are being proposed and implemented to influence carbon-management practices for mitigating climate change. Such policies rarely acknowledge biophysical factors, such as reflectivity, evaporation, and surface roughness, even though these factors can alter temperatures as much or more than carbon sequestration does - reducing or even canceling the benefits of carbon sequestration in some cases (Jackson et al. 2008). Biophysical interactions should be factored into climate mitigation strategy in at least two ways—in designing carbon sequestration projects to achieve the greatest climate benefit and in comparing the costs and benefits of carbon sequestration with those of other mitigation activities (DeFries et al. 2002, Chapin et al. 2008). Adding biophysical effects into frameworks for evaluating carbon sequestration programs is a decadal-scale challenge, but formal rules are needed to account for biophysics in climate policy.

4.5.5 Related Issues

Understanding the impacts and benefits of carbon management policies will require linkages far beyond the traditional boundaries of the carbon-cycle science research community. Research communities investigating the human dimensions of climate change and carbon policies have been working in parallel with carbon cycle scientists. This goal, as well as our new Plan, calls for an unprecedented integration of the work conducted by these two communities.

4.6 Goal 6: 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.

One of the goals of this Program is to support decision-making at many different scales as society responds to the challenge of climate change. This sixth goal seeks to provide carbon-cycle information needed by decision makers, understand how decision-making affects the evolution of the carbon cycle, and determine how information about the carbon cycle can be relevant to policy decisions. As used here, the term “decision makers” is meant in its broadest sense to include the general public, stakeholders, policy makers, and many other groups. This goal recognizes the need to be anticipatory. The needs of decision makers a decade from now will not necessarily be the same as the needs they confront now and a goal of research needs to be to anticipate and probe so that we are prepared to confront tomorrow’s questions.

4.6.1 Motivation

Critical policy and business strategies to address climate change are currently being made, and sound and understandable carbon science information is needed for these deliberations. In addition, carbon-cycle science needs to be accessible and understandable to a broad audience, including the general public, to enable them to participate in decisions that affect carbon management. As carbon policies are advancing rapidly, in both the private and public sectors, carbon science stands at the threshold of informing decision-making at many scales. We propose an invigorated, interdisciplinary effort both to understand these decision-making contexts and to provide the science to aid decision-makers.

4.6.2 Progress over the last decade

Society is moving rapidly in ways that affect the Earth’s carbon balance, including pursuit of renewable energy, emissions trading policies, means for preserving stocks of carbon in soils and forests, such as the REDD program, and other policies that may change the composition of energy supply. The last decade has seen a greater integration of studies linking Earth-system components to assess carbon-cycle dynamics. For instance, carbon science has been critical for informing international policy positions on carbon source and sink accounting as well as questions of additionality, permanence, and stabilization through the IPCC process (e.g. IPCC 2006; Dilling 2007). In the United States, carbon-cycle science has also supported decision-making on national, state and local levels through individual projects as well as agency-wide efforts (e.g., the U.S. Forest Service). Although the importance of decision-support in carbon-cycle science has recognized before (e.g., Sarmiento and Wofsy, 1999; SOCCR 2007), current circumstances provide a unique opportunity for fulfilling this goal. Both carbon cycle scientists and decision makers are coming to recognize that decision support is an on-going dialogue and not an intermitted push or pull of information and research results.

4.6.3 Major uncertainties

Given the societal importance of decarbonizing the economy and preserving terrestrial carbon stores, there are many decision-making contexts that should be informed by carbon science at appropriate scales. One example is the set of uncertainties that surround geoengineering, including the net benefits for climate and the carbon cycle (Shepherd et al. 2009, Jackson and Salzman 2010). Another is the way in which economic development pathways and mitigation strategies interact with the carbon cycle, including the consequences of continued ocean acidification on economic productivity, the ways in which the development of carbon pricing affects energy and sequestration technologies, and issues related to the ownership and governance of sequestered carbon. The above-cited examples of developing biomass fuels and REDD are current areas where decision making is stymied by lack of clear analysis and guidance. Opportunities exist to build ongoing relationships with particular sectors and stakeholders in order to understand what carbon science is relevant and useful. Currently, major uncertainties remain for what types of science are needed to support decision making in a world where carbon emissions will be limited and this emphasizes the need for an on-going dialogue. It is in this realm too that there is an important need to be able to understand and convey the source and magnitude of uncertainty in our understanding of the carbon cycle.

4.6.4 Scientific directions

Characterize the fundamental dynamics of decision making as they affect large-scale trends and patterns in carbon stocks and flows

Identifying key processes and drivers that control carbon fluxes is central to studying carbon decision-making dynamics. In land-use decisions, for instance, drivers such as values, climate, global markets, economic pressures, and opportunities and policies at various scales are all important to decision makers (Richards et al. 2006). Decisions at various scales can and do intersect, and collectively they often result in emergent patterns of carbon storage or fluxes, depending on the interactions. In addition, a given policy direction can have unexpected results depending on the situation and receptivity of individual decision-makers to the policy, as well as interactions with global markets. In all likelihood, carbon management as a goal for decision makers will continue to be embedded within the context of multiple, sometimes competing goals, (Tschakert et al, 2008. Failey and Dilling, 2010).

Systematically address decision-maker needs for carbon-cycle-science information as they begin to incorporate carbon-related factors into their decision making

Several models exist of communities that have successfully devised approaches for making science "usable" for decision making. One example in a closely related field is the seasonal to interannual weather forecasting community. Overall, usable science is "science that is relevant to the decision context, that is available at the time and geographical scale of interest, and that can make a difference to the outcome of a decision" (Lemos and Morehouse 2005, Tschakert et al 2008, Dilling and Lemos, in revision). The four main requirements in making science useful for decision making are: a) to understand the context in which information is to be provided; b) to ensure the information produced is relevant to the decision and that realistic choices are available; c) to confirm that a receptive institutional, cultural, and organizational setting exists into which information can enter; and d) to establish that adequate information and delivery mechanisms are present. To create these conditions, an ongoing, two-way dialogue between researchers and decision-makers must be established early and maintained over time, in order to build trust and knowledge of what is possible scientifically, and of what is useful from a decision-making perspective (Morss et al. 2005, Lowery et al. 2009). There are many examples of carbon policy and decision making underway at present, and the challenge will be to identify those potential users who will benefit from direct linkages with the carbon cycle science community and who represent the best fit with the existing mandate of the carbon community for providing decision support. A series of pilot projects at various scales will be necessary to develop skills in this area so that a broader effort at improving decision-making can occur over time.

4.6.5 Related Issues

Research related to decision-making for carbon has been carried out beyond the carbon-cycle science community, in arenas such as economics, integrated assessment modeling, land-use and land-cover change, and even energy technology. However, these communities to date have not experienced much overlap with the carbon-cycle science community in research agendas, joint projects or shared questions. Integrating the knowledge and background of people from these other communities will be important for the success of Goal 6, including developing new areas of interdisciplinary research on decision making and the carbon cycle.

CHAPTER 5: Science Plan Elements

A number of key research components comprise the central core for advancing carbon-cycle science over the next decade. We group these cross-cutting components into four high priority elements: (1) sustained observations, (2) studies of system dynamics and function across scales, (3) modeling, prediction, and synthesis, and (4) communication and dissemination. These are the "action items" of the research agenda. Each of these elements contributes to all six of the goals described in the previous chapter and all four are critical to achieving each of the goals. In the text that follows, these elements are further subdivided to provide finer focus on the research needs. The descriptions of the elements given below provide details and examples of the types of research that are needed and how current research activities need to be enhanced to fully realize the goals stated above. The most critical priorities for each of these elements are highlighted in italics.

5.1 Sustained observations

The observational network for measuring and tracking carbon/climate is the backbone of the global carbon program. The measurement programs document the evolution of the carbon cycle in the atmosphere, terrestrial biosphere, and ocean, as well as the human systems that affect these carbon reservoirs. The key to an effective carbon/climate observational network is continuity of measurements, adequate spatial and temporal coverage, and the development of long-term records. Unlike weather data that are most valuable at the time of collection and become less useful over time, long-term records of climate- and carbon-relevant measurements become more valuable with time (e.g. the Mauna Loa atmospheric CO_2 record; see Tans, 2010).

Key components of such an integrated, sustained observation system are: Earth observing satellite observations of Earth-surface properties and atmospheric constituents, atmospheric observation networks (including flux, flask, tower, and airborne observations), open-ocean and coastal-ocean surface and subsurface sampling, field biomass monitoring data, and monitoring and assessment of human systems - including mitigation and adaptation strategies and associated impacts. All of these observations have an inherent time scale that has the greatest relevance for carbon cycle studies. For example, while some observations require near continuous measurements to fully document the variability others may require only thorough surveys every few years or even once per decade. We do not prescribe here what those time scales are or attempt to detail exhaustively the full breadth of the components described below.

One issue that is common to all of these networks is that data are often gathered through research projects with grant-driven funding cycles and spread across multiple agencies. While the research focus helps to ensure that the measurements are state-of-the-art and relevant to key research questions, it also means that these networks generally have uncertain long-term funding and limited coordination. *More stable funding options must be identified for the subset of these observations that form the backbone of our understanding and study of long-term carbon cycling dynamics.*

5.1.1 In situ atmospheric observations

Networks of observations that provide data on atmospheric CO_2 concentrations and related species, as well as plot-scale observations of carbon fluxes, are providing key long term data for carbon cycle science. These networks, however, will benefit from a more coordinated and integrated design, together with longer-term sustained funding for the key elements. Global carbon flux networks such as FLUXNET, and its American subset, AmeriFlux (ORNL, 2010), provide information on carbon sources and sinks in different terrestrial ecosystems. However, the individual sites in these networks are typically funded on a regular grant cycle and many sites are therefore being discontinued due to a lack of funding availability. The atmospheric CO_2 flask and tower network, coordinated by NOAA ESRL, is a cooperative network documenting atmospheric CO_2 trends but it too has issues of site continuity. NOAA ESRL also maintains regular aircraft-based atmospheric sampling at some sites, supplemented by additional data provided through investigator-led research projects.

A high-priority need in this area is to select and standardize a subset of flux, flask, tower, and aircraft sites coordinated as a permanent network with steady funding to ensure data continuity. The NSF funded NEON project (NEON, 2010) will fill a part of this need from the standpoint of flux observations over the next 5 years as it constructs 19 bio-climatologically defined domains that will each have 1-3 flux towers. This coordinated network should not only encompass existing observation sites, but must also expand key components. Additional tall towers that provide continuous CO_2 observations are needed to constrain the North American carbon cycle. Aircraft profiles and large-scale transects of atmospheric sampling also provide valuable regional scaling, and regular routing and time schedules would enhance the information that they provide.

In addition, although much of the emphasis has been on expanding and maintaining CO_2 observing capabilities, measurements of several other atmospheric species (including, but not limited to CH_4, CO, and carbon isotopes) also form a critical component of a stable observing network.

5.1.2 Ocean and terrestrial observing networks

Surface ocean carbon observations are currently made on research ships, volunteer observing ships (VOS), moorings, surface drifters and from satellites. The current *in situ* network is relatively strong in the North Atlantic and North Pacific but less so for other ocean basins. Interior ocean carbon observations have made good progress in documenting changes in ocean physics, carbon, and other tracers since the WOCE/JGOFS cruises of the 1990s (see NOAA, 2010), but needs to be maintained to understand ongoing changes. These observational networks are reasonably well coordinated but require a more stable long-term funding structure and ship time to help ensure their continuity and to build out the networks in under-sampled regions. Remote-sensing using a wide variety of instruments is critical for understanding global patterns of ocean physics (e.g. temperature, dynamic height), biology (e.g. ocean color), chemistry (e.g. salinity) and air-sea forcing properties (e.g. surface winds, wave height). Continuity and enhancement of these observations is imperative.

Although there are a number of measurement programs in coastal waters, very few have a carbon focus and there is almost no large-scale coordination. A coordinated biogeochemical observing network for US coastal waters would provide consistency in what is measured, the frequency of observations, and the reporting of data to national data centers. A US coastal observing program could build on existing infrastructure to coordinate observations that would not only continue to serve the local needs but also contribute to a large scale coastal carbon observational effort. *Overall, there is a high priority need to expand and enhance the open-ocean and coastal carbon observational networks.*

Furthermore, there is a high priority need to establish a measurement and observational effort aimed at understanding ocean acidification. The existing ocean interior observations do provide data relevant to large scale ocean acidification but the current surface observing network is geared primarily toward quantifying air-sea gas exchange so it focuses on CO_2 partial pressure measurements. To constrain the observations of changes associated with ocean acidification the network needs to be enhanced to add a second carbon parameter and supporting biological observations in the surface ocean. The coastal network described above should also provide the information needed on ocean acidification in the coastal regions. Special attention should be focused on observing and tracking the process and impacts of ocean acidification in particularly vulnerable environments such as coral reefs.

The best current terrestrial inventory system in the United States is the USDA Forest Service Forest Inventory and Analysis (FIA) program, which evolved from the permanent forest growth plot data of the

US Forest Service (USDA Forest Service, 2010). An equivalent regular inventory of agricultural and rangeland soil and ecosystem carbon needs to be developed to provide a more comprehensive view of land-based carbon stocks. Together with the flux tower observations described in the sub-element on satellite and atmospheric observations, such measurements would provide critical understanding of the biospheric component of the carbon cycle in North America and globally. Such observations should be closely coordinated with related observations being made internationally to maximize the impact of the overall observational effort.

Overall, there is a need to establish and standardize regular cross-agency observations of terrestrial carbon variables for forests, agricultural lands, and rangelands, and to establish a more comprehensive land- and satellite-based network to assess land-use effects on the carbon cycle.

5.1.3 Satellite observations

Earth observing satellites provide global data at high spatial and temporal frequencies. These data allow scientists to evaluate the spatial and temporal patterns in the carbon system in a manner that would not be feasible using only *in situ* observations and/or airborne remote-sensing. Just like for *in situ* observations, the usefulness of satellite observations is only fully realized by ensuring continuity in the data records of critical atmospheric and Earth surface observations. Given the relatively long development cycles and high cost of satellite missions, long term commitment and advanced planning is necessary for ensuring data continuity.

A comprehensive list and description of current and upcoming Earth observing satellites that will contribute to carbon cycle science is beyond the scope of this Plan. One recent review of mission needs and capabilities is available as part of the GEO Carbon Strategy report (Ciais et al., 2010). A brief set of examples is presented below.

Many critical Earth observing satellites from the NASA Earth Observing System (EOS) platforms are nearing the end of their operational lifetimes. Many of these satellites provide observations of greenhouse gases (Aqua, Aura) including mid-tropospheric CO_2 observations by the Atmospheric Infrared Sounder (AIRS) instrument on Aqua, as well as observations of Earth surface properties necessary for assessing carbon stocks (Landsat-7, Terra, Aqua, Sea-viewing Wide Field-of-view Sensor (SeaWiFS)). Observations from instruments aboard these platforms have played a central role in informing carbon cycle science research over the last decade, and will continue to do so for the lifetime of these missions. Given the need for data continuity outlined above, transition to the Joint Polar Satellite System (JPSS) operational platform will be a critical activity in the coming decade. Missions such as the Visible Infrared Imager Radiometer Suite (VIIRS) satellite will be important elements of this new suite of satellites that will inform carbon cycle science. Algorithms and data products from current instruments will need to be replicated using the new generation of instruments. In addition, data processing systems will need to be developed for JPSS that are compatible with existing datasets. Taken together these steps will provide continuity for detecting changes in the carbon cycle.

Several other missions currently in the planning and development phases will provide critical additional data for carbon cycle science in the coming decade. Missions currently in formulation and implementation that will make it possible to assess carbon stocks through Earth surface observations include the Landsat Data Continuity Mission (LDCM), the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP) satellite, and the Ice, Cloud,and land Elevation Satellite-2 (ICESAT-2). The Soil Moisture Active and Passive (SMAP) satellite will also provide key ancillary information. In addition, missions capable of providing space-based observations of atmospheric CO_2 will provide a key complement to the existing *in situ* network of flask, tower, and airborne atmospheric observations. The Orbiting Carbon Observatory (OCO), the first NASA mission designed specifically for making CO_2 observations from space, was lost at launch in February 2009. The instrument is currently being rebuilt as OCO-2.

Furthermore, the NRC Decadal Survey (National Research Council, 2007) recommended the development of several satellites that will begin to provide high-value observations for carbon cycle science in the next decade or, in some cases, shortly thereafter. The ICESAT-2 and SMAP satellites mentioned above are part of this decadal plan. Additional missions that will provide information on Earth surface properties that will be used to assess carbon stocks and flows include the Deformation, Ecosystem Structure and Dynamics of Ice (DESDynI), the Hyperspectral Infrared Imager (HyspIRI) satellite, the Aerosol – Cloud - Ecosystems (ACE) satellite, the Geostationary Coastal and Air Pollution Events (GEO-CAPE) satellite, and the Lidar Surface Topography (LIST) satellite. Supporting observations will also be provided by the Snow and Cold Land Processes (SCLP) satellite. In addition, the Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) satellite will provide the next generation of satellite-based CO_2 observations. The DESDynI and ASCENDS missions were recently recommended for accelerated development.

Finally, international missions offer an opportunity for further expanding our understanding of key processes governing the global carbon cycle. Two examples of such missions include the Japanese Greenhouse gas Observing SATellite (GOSAT; NIES, 2010) and the Advanced Land Observing Satellite (ALOS) and its Phased Array type L-band Synthetic Aperture Radar (PALSAR) instrument.

A high-priority activity is to establish long-term continuity of critical satellite-based datasets, including observations of both Earth-surface properties and atmospheric constituents critical to improving our understanding of the carbon cycle.

5.1.4 Monitoring and assessment of human systems, including mitigation and adaptation strategies and associated impacts

Sustained data collection and monitoring of human activities resulting in CO_2 and CH_4 emissions are critical for understanding the patterns of CO_2 uptake and release. A broad range of demographic, economic, and technologic data are critical for understanding, projecting, and potentially managing the human role in the global carbon cycle. Synthesis and attribution projects that rely on a steady stream of local and regional information on human activities to attribute emissions to various sectors are an important element in this monitoring effort. Separation of the human and “natural” components of the carbon cycle depends on understanding both at the same temporal and spatial scales.

In addition, many local, state, and regional mitigation and adaptation strategies are being developed to reduce carbon footprints and respond to climate change. As these strategies are implemented, they need to be monitored to determine their effectiveness and to identify any potential side effects. A large scale data collection effort can be used to inform small scale mitigation and adaptation projects of what strategies are most effective and cost efficient.

Of all the sub-elements listed above, this priority on human systems is the least developed in the scientific community and requires substantial new resources to develop and coordinate. Funds should prioritize integrated social and natural science projects where appropriate.

5.1.5 Mapping sustained observations into the goals

The observations that comprise this element contribute to all of the stated goals, but are most central to Goal 1. One cannot have a clear and timely explanation of past and current variations observed in atmospheric CO_2 and CH_4 without knowing what those variations are or how the other reservoirs and drivers have changed over time. Observations are needed over a range of temporal and space scales to more effectively attribute observed changes to particular processes. Sustained observations are also needed for Goal 2. The human-system observations are critical for understanding the socio-economic drivers of emissions, and all components of this element are needed for monitoring and verifying emissions. Fossil fuel and land use observations coupled with natural science observations are needed to estimate emissions and to provide independent assessments of those emissions. Knowing the history and records of change of the pools will help provide understanding of potential vulnerabilities as a component of Goal 3 and how ecosystems are changing for Goal 4. Observations of human activity will also provide information on how human systems are changing as a result of increasing awareness of vulnerabilities. Quantifying the amount of carbon in plants and other organisms globally will also help to determine which components of ecosystems are most vulnerable to rising CO_2. Goal 5 requires sustained observations to document the results of what has happened under different management strategies, including how effective the strategy was and how humans have responded to the strategies. Finally, through Goal 6, decision makers will rely on observations to confirm that their decisions are having the desired effect.

5.2 Process studies of system dynamics and function across scales

Quantitative understanding of processes that affect carbon-cycle dynamics across a spectrum of spatial and temporal scales is important for diagnosing and predicting how the carbon cycle responds to changes in fossil fuel use, carbon management policies, atmospheric composition, climate, nutrient availability, disturbance, land management, and other drivers. Our understanding of how the carbon dynamics of human, terrestrial and ocean systems respond to, and interact with, changes in these drivers is incomplete. This is evidenced by the wide range of predictions of the future carbon balance of the terrestrial and ocean systems, as well as that of the future anthropogenic carbon emissions.

Process studies are critical for achieving each of the six goals outlined in this Plan. These studies include efforts to provide the mechanistic understanding for improving diagnostic and prognostic models of the carbon cycle. Manipulative experiments are an important complement to observational process studies of the current state of the carbon cycle for two reasons. First, experimental studies extend process studies into environmental and socioeconomic conditions that may occur in the future, challenging our mechanistic understanding of how the carbon cycle will function in altered environments. Second, manipulative experiments and process studies provide complementary understanding for informing and parameterizing the response of predictive carbon cycle models to evolving environmental drivers. Process studies will alert us when changes in the carbon cycle, the climate, or their consequences imply either positive or negative consequences for natural or economic systems.

5.2.1 Intensive process studies and field campaigns to observe and understand natural and human systems and the processes controlling carbon emissions, uptake, and storage

A major challenge is to conduct intensive process studies across traditional disciplinary boundaries to observe and understand the controls over carbon emissions, uptake, and storage. *Process studies need to be designed to fill basic research gaps on land and in the ocean (including of systems with potential for large loss of stored carbon), and to integrate how socioeconomic issues influence human impacts on carbon uptake and storage.* Integrating human impacts on the carbon cycle with traditional physical and biological observational studies is vital as human activities are now major global controls of CO_2, CH_4, and CO emissions to the atmosphere.

In terrestrial systems the development of improved understanding of the carbon cycle requires sustained observations in ecosystems vulnerable to carbon loss, including permafrost, forests, and locations with methane hydrates, as well as for understanding the processes responsible for human fossil fuel use, waste streams, land use, and land management. The impacts of human activities are linked to storage of carbon in the ocean and terrestrial ecosystems, which are influenced by changes in atmospheric composition, nitrogen cycling, climate, disturbance regimes, land management, and factors affecting methane emissions.

Similarly, many basic aspects of the ocean carbon cycle are inadequately understood, which reduces our ability to project the net oceanic carbon balance in the future and to assess the effectiveness of potential carbon management scenarios. Important processes that need to be better defined include gas exchange and the rate of anthropogenic carbon transport from the mixed layer into the thermocline and deep ocean. Also important is the role of biological processes in determining the spatial and temporal variability of air-sea fluxes and anthropogenic carbon uptake and storage. A deeper understanding of what controls the biological pump in the ocean is required, including the role of micronutrients and CO_2 in controlling productivity, controls on export of organic material from the surface, and transformations of organic material below the sunlit surface layer of the ocean.

Linking terrestrial and ocean systems is another important challenge for better understanding of how carbon, nutrients, and sediments are moved from terrestrial ecosystems through estuaries to the ocean, where the fate of carbon can be long-term storage in the marine environment or release to the atmosphere as CO_2. It is also important to monitor and understand the transport of carbon into and through rivers and other freshwater networks, the transformations of these constituents in these networks, and the delivery and fate of this carbon in deltas and coastal ecosystems; including the processes that control the conversion and loss of carbon in coastal oceans and along continental margins.

5.2.2 Manipulative laboratory and field studies to elucidate the response of land and marine ecosystems to climate, biogeochemical, and socioeconomic change and to deliberate carbon management

Much progress has been made in the last two decades in studying responses of terrestrial and ocean ecosystems to manipulations of individual climatic factors. For example, studies examining the effect of elevated CO_2 on marine organisms have been critical for assessing the potential impacts of ocean acidification. Likewise, the Free Air CO_2 Enrichment (FACE) studies have helped us to better understand CO_2 fertilization in the terrestrial environment.

Despite such progress, different responses observed across studies can be hard to attribute to changes in CO_2 as opposed to interactions with other environmental variables or to differences in experimental protocols. A reconciliation of the observed responses to manipulative experiments is particularly important for distinguishing natural variability from human-induced changes to the terrestrial and aquatic carbon cycles.

In addition to manipulations of the physical and biological environment, manipulative experiments are needed to test human decision-making associated with the carbon cycle and carbon incentives. Such manipulative studies should include research on human behavior, natural resource economics, and other areas of socioeconomic systems related to the carbon cycle.

Thus, manipulation experiments with common protocols that span broad environmental and socioeconomic gradients and that simultaneously manipulate multiple factors are needed. The focus of these studies should be to understand the responses of the net carbon balance to changing environmental conditions and socioeconomic drivers for carbon sequestration and other direct manipulations of the carbon cycle.

Some cross-disciplinary process studies and multi-factor manipulative experiments should be located in regions where the responses to manipulation are likely to reveal vulnerabilities in carbon storage (e.g. permafrost ecosystems). In order to identify system vulnerabilities, these studies must not only focus on systems that have already been identified as having potential tipping points in their ability to store carbon, but should also include systems that have yet to be examined. Given finite resources, it will be important for the scientific community to prioritize the focus of a new generation of process studies and manipulative experiments.

5.2.3 Integrative field campaigns to provide intensive data or test different approaches for examining carbon cycling at a range of nested scales

The Interim synthesis activities currently being conducted through the North American Carbon Program are providing a first, key opportunity to coordinate field campaigns and modeling efforts to reconcile understanding of carbon cycling for particular systems across a range of nested scales. The most mature of these is currently the Mid-Continent Intensive (NACP, 2010a), which represents a coordinated effort of field and airborne observations, atmospheric observations, inventory development, biospheric modeling, and atmospheric inverse modeling to improve understanding of carbon cycling in the agricultural Midwest region.

Related efforts focusing on coastal and other systems are currently beginning. These types of efforts will provide a key opportunity to synthesize understanding gleaned through carbon cycle studies over the past several decades by providing a platform for integrating different types of data across different spatial and temporal scales, and obtained through a variety of mechanisms. Such efforts need to be supported independently of more focused observational studies and modeling approaches, to provide a clear opportunity for synthesis across the carbon cycle science community.

Another area of opportunity is to have integrated field campaigns include tests of human decision-making and other socio-economic factors of how people affect the carbon cycle. For instance, the Large-scale Biosphere-Atmosphere Experiment in Amazonia examined how Amazonia functions as a regional entity within the larger Earth system as well as how changes in land use and climate affect the biological, physical, and chemical functioning of the region's ecosystem. Socioeconomic factors have not traditionally been part of similar research campaigns. In the future campaigns should combine critical data needs in the physical and biological sciences with relevant socioeconomic data in the same locations. For instance, campaigns could quantify the human factors that drive changes in land use, fish catches, or other factors relevant to productivity and the carbon cycle. More integrative field campaigns are needed to test different approaches for examining carbon cycling at a range of nested scales.

5.2.4 Mapping studies of system dynamics and functions into the goals

The studies in this element contribute significantly to all of the stated goals. Understanding processes is a key part of providing a clear and timely explanation of the mechanisms behind past and current variations in atmospheric CO_2 and CH_4, as stated in Goal 1. These studies will also help determine realistic uncertainty estimates by placing bounds on mechanisms and responses. An understanding of system dynamics is central to understanding the socioeconomic drivers of carbon emissions in Goal 2. New socioeconomic components of Element 5.2 include manipulative experiments to test human decision-making for carbon incentives and extending traditional gradient studies from biophysical variables to socioeconomic ones. Goal 3 calls for an understanding of vulnerabilities and prediction of future carbon cycle changes that can only be achieved with a process level understanding of biological, physical, and socioeconomic systems. Process studies are also central to interactions of the changing carbon cycle and climate with ecosystems, biodiversity, and natural resources, the core of Goal 4. The carbon cycle is intimately linked to ecosystem services that people value, including water resources and biodiversity. The theme of ecosystem services extends to Goal 5, which examines the side effects of carbon-management pathways, another area for which process-level observations and manipulations are central. Process measurements associated with carbon-management experiments will provide mechanisms and likely outcomes for different carbon-management alternatives. Finally, Goals 5 and 6 together, including the needs of decision makers for carbon-cycle information, require an improved understanding of human choices and the responses of the natural environment to those choices. These can only be achieved with an understanding of integrated system dynamics.

5.3 Modeling, prediction, and synthesis

Numerical and statistical modeling has been an important component of carbon cycle research over the past decade and will continue to play a central role over the next decade. Modeling studies provide unique opportunities for data analysis, mechanistic exploration, and prediction of human and natural interactions across scales of space and time. Models can also form the backbone for synthesis. Inter-comparison activities that merge inventory and site-level data with the mechanistic relationships embodied in the models themselves provide opportunity to understand core processes and to evaluate the uncertainty in our understanding. These syntheses push forward our process-level understanding of the carbon cycle and are critical for identifying knowledge gaps.

In each of the elements described in this section, particular emphasis needs to be placed on quantifying and/or reducing uncertainty. In the current context, quantifying uncertainty goes beyond assigning traditional error bars that represent the sensitivity of model results to specific parameters or model-generated uncertainties based on statistical assumptions built into the modeling framework. *Instead, significant effort needs to be invested in developing methods for uncertainty quantification that reflect all sources of uncertainty affecting a particular model estimate.* Such objective levels of scientific understanding can be used to communicate scientific results quantitatively, or even qualitatively, both within and beyond the carbon cycle science community. Once appropriate tools are available for uncertainty quantification, the process of uncertainty reduction through model development, improved observations, and model evaluation becomes a meaningful way of tracking the evolution of the state of the science. Characterization of uncertainty can be useful in guiding decision making.

In the realm of global change there is great interest in predicting and anticipating the future. Modeling and synthesis activities are critical to our skill in predicting the future but there is always inherent uncertainty in any predictions. There is a need to develop and present realistic and useful ways to convey the uncertainty of projections, the range and distribution of potential outcomes, and the consequences of uncertainty.

5.3.1 Improve existing models

Numerical models of the Earth System, such as those used for the IPCC assessment process, are computer codes that attempt to fully represent the evolving climate system and to predict its future state. These models can be used in hind-cast mode, looking backward, to represent the past climate, and then their predictive success can be tested through comparisons to historic data. Such efforts have identified a host of outstanding issues with Earth System models, most of which derive from the lack of fundamental understanding about physical or biogeochemical processes.

In the next decade, model skill needs to be improved through enhanced collaboration of field, laboratory, and modeling scientists. Many ongoing model development efforts should continue in the upcoming decade. Additional effort will need to be invested in developing models that bridge and synthesize information across traditional disciplines and data types. For example, improved models that link coupled land-(coastal) ocean models at regional scales are needed to better understand this important area where land, ocean, atmosphere, and humans interact on very small scales. Smaller projects focused on particular processes are needed. In addition, targeted programs promoting model-model and model-data comparison can be particularly useful to identifying fundamental knowledge gaps. Process studies (element 5.2) will provide critical mechanistic information that can be used to improve model parameterizations.

The complexity of Earth System Models makes them enormously computationally intensive. There are some model processes that can best be improved by increasing model resolution and there are additional, highly complex modules that need to be included. Thus, we should expect Earth System Models to continue to stress computational resources in the next decade. *Innovative computing strategies that will make this software run faster or make the hardware more powerful should be pursued.*

In order to explain observed variability and trends in the atmospheric CO_2 concentration (Goal 1) and track carbon emissions and sequestration activities in land and in aquatic systems (Goal 2) we must have optimal diagnoses of the current state of the carbon cycle and the mechanisms driving variability and change. Models that allow for the integration of multiple sources of data and information offer the opportunity to provide these accurate assessments. The continued evolution of parameterization approaches for process-based models, the ongoing improvements to the statistical framework of inverse models, and the ability of all models to ingest a wider variety of data types (as well as the recent early steps in integrating computational approaches based on numerical data assimilation) are all providing opportunities for such explicit integration of data across types and scales. Much work will be needed over the next decade to develop the necessary conceptual, numerical, and statistical tools to fully benefit our community and to make optimal use of the expanding set of observations available for informing our understanding of the carbon cycle.

5.3.2 Add human dimensions to Earth System Models

Integrated Earth System models are extremely complex because they ideally strive to include the entire range of processes and feedbacks across the spectrum of human and natural processes. Development of these models in the last decade has focused on physical parameterizations and great strides in representation of biogeochemistry have also been made. These models must continue to be developed, as outlined above. *In addition, however, more complete and complex representations of human activity are needed in Earth System Models.* Trends and distribution patterns in demographics, migration, international trade, economic development, human settlements, world view, transportation technology, agricultural practice, and materials substitution only begin to enumerate (much less quantify) the multitude of factors that will impact and/or be impacted by the global carbon cycle and efforts to manage the human perturbation of the carbon cycle. The available alternatives, advertent and inadvertent incentives, and choices faced by people and the feedbacks from the climate system will have huge impacts on the path of change in the global carbon cycle. It is increasingly important to know what we can know and to deal with what we do not or cannot know. Modeling and analytical systems can begin to represent the interactions and side effects of the multitude of interacting factors and to identify the critical parameters and inter-linkages.

Finally, the needs of decision makers need to be considered as models are developed and simulations are planned. Interactions with decision makers are needed both to frame the questions for research and to pursue the answers from research. These efforts will require new frameworks and centers for trans-disciplinary collaboration as well as a renewed commitment to data management and computational resources.

5.3.3 Augment synthesis activities

Synthesis brings together data products and models that attempt to capture similar or related processes and evaluates the degree of agreement between the different data and modeling approaches. Synthesis efforts are critically important to identifying gaps in knowledge and for leading to new studies to fill those gaps. However, synthesis activities are often difficult to fund from science budgets, largely because they are generally not “new” science. *Funding strategies to support critical synthesis activities are needed.*

The 1999 U.S. Carbon Cycle Science Plan led to the North American Carbon Program. The NACP's current Interim Synthesis is a dramatic example of the power of the synthesis and inter-comparison process. Currently, as part of the NACP's interim site synthesis activities (NACP, 2010b), tens of models are being compared to data at tens of locations. In addition to enhancing knowledge of terrestrial carbon cycle processes, this activity is making it possible to identify critical differences among models. This process could not occur without facilitation by the MAST-DC (NACP, 2010b), a dedicated carbon cycle modeling and data synthesis center that is standardizing formats and providing repositories for community data sets and model results. Similar to NACP's current Interim Synthesis effort, *coordinated synthesis efforts are needed for the open ocean, the coastal zone, the entire land to deep ocean system, and integrated human-natural assessments.*

5.3.4 Mapping of modeling, prediction, and synthesis into the goals

Modeling and synthesis are essential for the successful achievement of all six goals of the Plan. Many kinds of models will contribute to the goals, including process-based models, atmospheric and oceanic inverse models, flux inventories, and tools for numerical data assimilation that are increasingly being used to parameterize models,. Models and simulations already help to explain variability and trends in past and current atmospheric CO_2 and CH_4 concentrations (Goal 1) and project greenhouse gas concentrations into the future. Models are also needed to track the socioeconomic drivers behind carbon emissions and sequestration (Goal 2). Vulnerabilities in carbon stocks, such as permafrost loss and critical feedbacks with biodiversity and other ecosystem services, all need to be characterized through experiments and model simulations (Goals 3 and 4). In addition, interactions across the scientific and decision-making communities will be critical for analyzing the efficacy of carbon-management strategies and for the effective use of analyses and predictions (Goals 5 and 6). Although modeling of the physical environment, in particular, has made tremendous strides over the last decade, models that more accurately represent biologically driven processes and human interactions are needed to address complex carbon cycle interactions and to quantify accurately the current uncertainties associated with our understanding of components of the global carbon system.

5.4 Communication and dissemination

Effective communication and dissemination of the results of carbon cycle science research are essential if the investments made in science are to become useful in other studies and in informing decision making and conservation efforts. Communication is, of course, a two-way street and in this time of increasing concern about climate change it is important that scientists not only communicate their results but that they are receptive and attentive to the output of other disciplines and the needs of decision makers and the general public. There are significant benefits to be gained by working with established efforts to take advantage of knowledge across disciplines but it is also important to recognize that publication in the peer reviewed literature is a necessary but not sufficient vehicle for communicating the needs and results of research. Communication and dissemination of science is a confusing issue at times because it is not necessary or appropriate that every scientist reach out and communicate with the public, but it is necessary that some scientists bridge the gap between the laboratory and peer reviewed technical literature and the decision makers and public who use the results and support the conduct of science. Science is the pursuit of knowledge but it has an obligation to meet the goal of serving individuals outside the immediate natural science research community and of helping society to make informed decisions. This includes communication within the US as well as with the international community.

The sub-elements described in this section encompass key aspects that will enhance the impact and responsiveness of the research conducted within the scope of the Plan. These aspects include an emphasis on two-way communication with the broader community, the translation of scientific results into quantitative information that is directly usable by related communities, and the promotion of better understanding by the scientific community of the decision-making process. These aspects need to be considered within the broad context of quantifying and expressing uncertainty in a manner that is both useful and relevant to communities that make use of carbon cycle science research outcomes, and helping those communities assess the impacts of those uncertainties on their own work and planning.

5.4.1 Establish dialogue among decision-making community, general public, and scientific community

For many, the term communication conjures up images of pamphlets, websites, or lectures designed to bring the most important results of research to a wider audience. Communication research shows, however, that this sort of passive, one-way communication is rarely successful at promoting the integration of new knowledge into practice so that it can make a difference and change outcomes (e.g., Lemos and Morehouse, 2005; Moser and Dilling, 2007). Communication and dissemination strategies can fail on many grounds -- because the information is not relevant to a decision, because the information presented is confusing or not understandable to the audience, or simply because the channel used to disseminate information is not well attended by the intended audience. When addressing an international audience cultural perspective can also complicate effective communication of information. These findings suggest that it is worth the time up front to think carefully about how to craft a communication strategy and to invest in research to refine communication efforts such that they can be most effective.

Perhaps one of the most common truisms in communication is the exhortation “know thy audience.” Only by knowing whom the intended audience will we know what matters to them. Carbon cycle science is a relatively complex subject to discuss, and yet one that intersects every person’s life through the decisions he or she makes. *As part of an ongoing strategy to ensure that carbon cycle science is relevant to decision making, decision makers and researchers need to create new mechanisms for co-producing information on what decisions affect the carbon cycle and how decision contexts can incorporate the new knowledge generated through carbon cycle science.* As part of this process, researchers will learn what is important to decision makers and decision makers will learn what science can and cannot provide at their scale and context.

As part of this element the scientific community needs to work in tandem with communities outside the carbon cycle science research community both in the US and abroad to establish whom the target audience and potential users are for the results of carbon cycle research. There may be several audiences, from sophisticated policy analysts to individuals trying to understand voluntary offset programs.

In addition, the implementation of this Plan needs to create a communication focus up front as an ongoing part of the program, and to ensure that this focus is kept throughout the process of implementing the Plan.

5.4.2 Develop appropriate tools for communicating scientific knowledge to decision makers

It is imperative that the research conducted as a result of this Plan yield tools that translate results from scientific synthesis and prediction into quantitative, understandable products for policy and management professionals. Knowing the ultimate audience for scientific results means knowing how they access and understand new information. All too often scientific programs tend to have a “loading dock” mentality to the production of information, which entails creating the information, putting it on the loading dock, and assuming or hoping that someone will come and pick it up (Cash et al. 2006). The “loading dock” of science is usually peer-reviewed journals, which are necessary for the process of science, but which are also largely inaccessible to the majority of decision makers and even less so to the broader public or international groups. *Through the upcoming decade, other mechanisms of reaching decision makers with information must be engaged, including different types of trade meetings, workshops, newsletters, and outreach networks.*

In addition, the carbon cycle science community needs to study how management options are being evaluated in the US and abroad, what questions are being asked, and how best to provide information that is useful to policy makers at the time that they need it. This will allow the carbon cycle science community to determine how management options are being evaluated and how the carbon science community can help inform that process.

5.4.3 Evaluate impact of scientific uncertainty on decision makers

New approaches are needed for effectively communicating the level of certainty that scientists have in various components of the carbon budget to managers, decision-makers, and the general public. The graphics and flowcharts that are currently typical of carbon cycle science are not intuitively understandable to the general public. The carbon cycle science community has an opportunity to more effectively communicate scientific uncertainty to decision makers by engaging communications researchers from other scientific communities. These communities include the seasonal to inter-annual forecast community, the weather research community, and the climate forecasting community. For example, researchers in the climate arena have studied for years how to present the notion of probabilities, in such a way that forecasts can be properly understood in the context of the range of uncertainty, rather than as a deterministic single prediction of the future. The graphics used in endeavors such as drought monitoring, weather forecasting and seasonal to inter-annual climate forecasts are tested and refined based on experience and feedback from users As carbon cycle science becomes increasingly relevant to decision makers, this community will need to develop and test creative ways of reporting findings so that the intended meaning is received.

As effective methods for communicating uncertainty are developed, the carbon cycle science community must also work together with the broader public to evaluate the implications of uncertainty in present-day knowledge and in future carbon cycle projections. In order to prioritize research needs from the perspective of decision-maker and public needs, there is a need to develop tools for assessing the implications of different levels of uncertainty on the ability of decision-makers, the general public, and others, to make effective use of the information provided. This does not imply that all research could or should be prioritized based on such a criterion, but such an approach is needed for research that is directly intended to address the needs of a specific audience, whether it be decision-makers, the general public, or others.

5.4.4 Mapping communication and dissemination into the goals

The communication and dissemination activities described in this element contribute to all of the stated goals. The clear and timely explanation of past and current variations observed in atmospheric CO_2 and CH_4 (Goal 1) includes effective communication with communities beyond carbon cycle science as well as the development of appropriate tools for communicating scientific knowledge and its associated uncertainties. Understanding and quantifying the socio-economic drivers of carbon emissions and developing transparent methods to monitor and verify those emissions (Goal 2) also requires the establishment of a two-way dialogue between the carbon cycle science community and decision makers, as well as the development of tools for effectively communicating scientific understanding with this community and learning the questions being confronted by this community. The ability to learn and evaluate the impact of uncertainty on decision makers can inform research on determining and evaluating the vulnerability of carbon stocks and flows to future climate change and human activity (Goal 3). Similarly, the goal of predicting how ecosystems, biodiversity, and natural resources will change under different CO_2 and climate change scenarios (Goal 4) will have a larger impact if appropriate tools for communicating scientific knowledge are available. If we are to determine the likelihood of success and the potential for side effects of carbon-management pathways (Goal 5), it is essential to understand and evaluate the impact of scientific uncertainty on this decision-making process. Finally, the goal of addressing decision-maker needs for current and future carbon-cycle information, and providing data and projections that are relevant, credible, and legitimate for their decisions (Goal 6), requires an appreciation of their questions and concerns and is directly dependent both on the ability to effectively communicate scientific knowledge to decision makers and to evaluate and communicate an objective sense of the impact of scientific uncertainty on the decision-making process and its goals.

5.5 Resource requirements

The current state of carbon cycle science, together with the four research elements identified above, begins to outline a coherent, integrated research program with priorities that include both existing and new components. Significant new resources are needed to continue with high priority, existing initiatives, to reach out in important new directions, and to accelerate progress toward confronting a problem the relevance of which to human welfare is becoming increasingly apparent. Our ability to reach the stated goals within the next decade will depend heavily on the ability of the U.S. funding agencies to provide full financial support to the Plan. The 2009 edition of *Our Changing Planet* report to Congress estimated that the total U.S. carbon cycle science budget is currently about $170 million per year (USGCRP, 2009). While this budget had grown substantially over the last 5 years, many of the observing networks, process studies and model development efforts are at less than half of the levels necessary to understand the global carbon cycle at the required level of detail for effective management decisions. Integration of the human dimensions components of the carbon cycle has not been possible with the current level of funding, and very few resources have been devoted to communication and dissemination, making the path and time required for new research findings to inform management decisions extremely inefficient.

Many of the planning documents listed in Chapter 2 include detailed budgets for the implementation of their components of carbon cycle research. Using these detailed budgets, the budget compiled for the 1999 Science Plan and an assessment of what the carbon cycle community has accomplished with the current levels of funding, we estimate that the total U.S. carbon cycle budget will need to be increased to approximately $500 million per year to achieve the goals outlined in this Plan. The distribution of these funds into the four elements described in the previous sections is recommended to be on the order of:

- $175M for the sustained observations element
- $125M for the process studies element
- $150M for the modeling and synthesis element
- $50M for the communications and dissemination element

The distribution of these funds to more specific research components is beyond the scope of this Plan and should be outlined as implementation strategies are developed for the various components of the Plan.

CHAPTER 6: Interdisciplinary and International Collaboration and Cooperation

This Plan recognizes the critical role that carbon cycle science is currently playing as interest in, and concern about, climate change become central issues in human considerations. Carbon cycle science plays a central role in understanding the Earth's climate system and in human considerations of how to manage long-term global change. Carbon cycle science is not an arcane subject at the margin of human affairs, but is rather a topic of general interest and of great need for environmental, economic, and human health. The boundaries of carbon cycle science are no longer just biogeochemical, but include linkages to the environmental, economic, and social sciences and to international affairs and public policy. The system boundaries of what is considered to be "carbon cycle science" are blurring as we recognize these linkages and the need for collaboration, cooperation, and the sharing of ideas and research results. Research in the traditional atmospheric, marine, and terrestrial aspects of the carbon cycle remain vital, but we are increasingly aware that there are human dimensions to the carbon cycle and that carbon cycle science impinges directly on issues of economics, engineering, and public policy. As managing the carbon cycle becomes increasingly common, institutional issues become important and the need for understanding and dealing with uncertainty become central.

The geographic boundaries within carbon cycle science are similarly blurring. What happens in the boreal tundra, the tropical forests, the coral reefs, and the global ocean affect us all – and these ecosystems are affected by all of us. It is increasingly apparent, also, that issues of the global carbon cycle are global in every sense of the word and that research supported by U.S. interests needs to be cognizant of and collaborative with research efforts around the world. Examples of key international carbon-cycle organizations include the Global Carbon Project and the Group on Earth Observations, coordinating efforts to build a Global Earth Observation System of Systems.

The U.S. has been, and must continue to be, a leader of and major contributor to international research efforts; but the US cannot bear the full burden. Measurement and monitoring of global change needs broad global effort and the full range of carbon cycle studies finds able colleagues and collaborators in many countries. The variety of social, cultural, and legal systems on Earth create a diversity of interests for understanding the human impact on climate and the human capacity for mitigating or adapting to changes in the carbon cycle. The U.S. educational system plays a major role in preparing the world's science community.

6.1 Interdisciplinary collaboration and cooperation

The challenge today is to broaden and redefine the boundaries of carbon cycle science; to build the linkages with research areas with common, interdependent, or overlapping concerns; and to ensure that critical topics or data needs do not drop into cracks between traditionally defined disciplines or sources of research support. We need to ensure that there is support for interdisciplinary and cross-disciplinary studies, and that human elements are incorporated into carbon-cycle studies whenever appropriate. Interdisciplinary studies and improved linkages with the social and political sciences are essential, and visions of the future need to be strengthened through interactions with integrated assessment studies and studies of carbon management. Research related to the development of biomass fuels, Reducing Emissions from Deforestation and forest Degradation (REDD), and the impacts of urbanization on coastal processes and marine resources are obvious examples of areas in which the human dimensions need to be a critical part of basic enquiries.

The future will require improved interaction and information exchange not only within and among different scientific disciplines, but also with stakeholders and decision makers – people who require up-to-date assessments, improved approaches for understanding complex and interdependent issues, and ways for quantifying and dealing with uncertainty. There is a need to bridge the differences between the research results published by scientists and the information needed by stakeholders and decision makers – to translate research findings into meaningful input for these groups. An ongoing dialogue among the different groups is needed 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.

6.2 International collaboration and cooperation

The increasing importance of international collaboration is also apparent. This Plan is envisioned for the U.S. based research community but the carbon cycle and its impacts are global and important studies are needed, for examples, in tropical and boreal areas, in the global oceans, and in other cultures. Observational networks, mitigation and adaptation strategies, predictions of the future, verification of commitments, etc., will all depend on participation and contributions from scientists around the world. The U.S. contributes importantly to international research efforts through its educational system and through access to unique information such as that provided by remote-sensing satellites and research vessels. U.S. scientists need to participate and take leadership roles in international assessments and syntheses, field campaigns, model inter-comparisons, and observational networks. All of these international participations offer opportunities to capitalize on other resources and to contribute the knowledge and creativity of U.S. scientists to coordinated research. Because of the benefits of international collaboration, this coordination should be realized for the full cycle from program planning to project execution and data management. While many international programs will involve large projects and efforts and multiple participants, opportunities for productive efforts also exist at the scientist-to-scientist level where cooperation with a single institution or exchanges of staff or students can facilitate or accelerate progress in critical geographic or disciplinary areas. U.S. scientists and students need to study abroad and U.S. institutions need to provide opportunities for scientists and students here.

There are numerous projects, opportunities and initiatives wherein researchers from many countries share data, insights, manpower, and platforms such as ships and satellites. We hesitate, for fear of important omissions, to list the many successful international research efforts currently focused on cooperation and collaboration among scientists from multiple countries, but we encourage thoughtful evaluation and U.S. participation whenever useful and when the whole is greater than the sum of the parts. U.S. scientists should be encouraged to take on leadership roles in these efforts. The Intergovernmental Panel on Climate Change can be cited as a example of scientists from around the world coming together to share information and views with the result of broad synthesis and important input to the decision-making process. There are many additional, more-focused collaborations that provide essential resources, synthesis, or intellectual support and where win-win situations result in the U.S. both giving and receiving important understanding.

6.3 Supporting and stimulating collaboration and cooperation

Research that is sensitive to the role of humans in the global carbon cycle, and the needs of people for carbon-cycle science can be facilitated by interagency working groups and advisory panels that include strong participation by human-dimensions researchers and social scientists. Specific research calls or pilot projects can be designed to encourage or require interdisciplinary collaboration beyond traditional alliances and interactions. Growing research initiatives, such as that on ocean acidification, should make pointed effort to ensure that human components and human needs are incorporated from the beginning.

In order to encourage or facilitate the kinds of interdisciplinary, international cooperative and collaborative projects needed, it may be appropriate for U.S. funding agencies to try innovative support structures, support targeted workshops, or issue specific calls for proposals that focus on areas in need of creative ideas to make progress. The kinds of mingling of ideas that are needed to solve interdisciplinary and global-scale problems are often non-traditional and specific measures may be needed to create the needed dynamics.

CHAPTER 7: Implementation and Funding

7.1 Integration of program priorities

Throughout this document, we have articulated long-term priorities for a new U.S. Carbon Cycle Science Plan, including the overriding scientific questions that drive the new Plan (see Chapter 3). The research goals in Chapter 4 represent specific research priorities that are derived from these long-term priorities and should be achievable within a 10 to 20 year timeframe, assuming that sufficient funding is available (see Section 7.3). The elements described in Chapter 5 cut across all of the goals and define priorities for specific, actionable components of the research plan. Each of the four top-level elements contributes to all six research goals, thus defining the cross-cutting building blocks needed to address the fundamental science questions outlined in this Plan.

Building on Chapter 5, which addressed how the individual elements build towards the goals outlined in Chapter 4, we present a complementary view in Table 7.1, examining how each goal draws on these elements. As the table indicates, each of the six goals relies on at least some components of each of the elements. While the text within the table in no way represents the full extent of the connection between the goals and the elements, this text clearly illustrates the interconnectivity of all the components of the Plan. Selectively funding specific components of the Plan while under-funding other components would degrade progress on all of the goals.

	E1: Sustained Observations				E2: Studies of System Dynamics and Function Across Scales		
	In situ atmospheric observations	**Ocean and terrestrial observing networks**	**Satellite observations**	**Monitoring & assessment of human systems**	**Intensive process studies & field campaigns**	**Manipulative lab and field studies**	**Integrative field campaigns**
G1: explain variations in atm. CO_2 and CH_4	document variations	document variations	document variations	helps explain drivers for variations	can confirm explanations of variations	investigate processes to help explain variations	provide link between process studies and observations
G2: Understand drivers and quantify emissions	document impact on atmosphere and some stock changes	document stock changes	document impact on atmosphere and some stock changes	informs socio-economic drivers of anthropogenic emissions	test theories on human drivers and quantification methods for emissions	test theories on human drivers and quantification methods for emissions	test approaches for quantifying emissions
G3: Evaluate carbon vulnerability	document changes in stocks and flows	document stock changes	document changes in stocks and flows	determines which stocks and flows may be impacted by humans	assess vulnerability	test specific vulnerabilities	assess vulnerabilities at regional scales
G4:Predict ecosystem changes	document ecosystem, biodiversity, and natural resource changes	document ecosystem, biodiversity, and natural resource changes	document ecosystem, biodiversity, and natural resource changes	informs possible carbon / climate scenarios	assess ecosystem responses and feedbacks	test ecosystem responses and feedbacks	assess responses and feedbacks at regional scales
G5: Evaluate carbon pathways	document impacts of current pathways	document impacts of current pathways	document impacts of current pathways	informs likely management pathways	assess impact of current pathways	test specific results of management decisions	assess impacts of pathways at regional scales
G6:Address needs for information	provide global information for decisions	document stock and ecosystem changes	provide global information, and document stock and ecosystem changes	provides information on decision-maker needs	provide information on local carbon cycle processes	provide information on impact of specific processes	provide information on regional carbon cycle processes

Table 7.1a: Mapping of the six science goals onto the first two of the four program elements.

	E3: Modeling, Prediction, Synthesis			E4: Communication, Dissemination		
	Improve existing models	**Add human dimensions to Earth System Models**	**Augment synthesis activities**	**Establish dialogue among communities**	**Tools for communicating scientific knowledge**	**Evaluate impact of uncertainty on decision-making**
G1: explain variations in atm. CO_2 and CH_4	quantifies fluxes and represents processes controlling variations	links human and natural processes	reconciles understanding across obs. / models	integrates understanding across communities	helps reach a broader community	identifies uncertainties that must be addressed
G2: Understand drivers and quantify emissions	improves emission assessments & prediction of socio-economic drivers	links humans with natural processes	reconciles understanding across obs. / models	integrates understanding across communities	helps reach a broader community	identifies uncertainties that must be addressed
G3: Evaluate carbon vulnerability	evaluates future responses	links humans with natural processes	reconciles understanding across obs. / models	integrates understanding across communities	helps reach a broader community	identifies uncertainties that must be addressed
G4:Predict ecosystem changes	evaluates future responses	links humans with natural processes	reconciles understanding across obs. / models	integrates understanding across communities	helps reach a broader community	identifies uncertainties that must be addressed
G5: Evaluate carbon pathways	evaluates future responses	links humans with natural processes	reconciles understanding across obs. / models	integrates understanding across communities	helps reach a broader community	identifies uncertainties that must be addressed
G6:Address needs for information	gives process diagnosis, attribution & prediction	links humans with natural processes	reconciles understanding across obs. / models	integrates understanding across communities	helps reach a broader community	identifies uncertainties that must be addressed

Table 7.1b: Mapping of the six science goals onto the second two of the four program elements.

7.2 Implementation opportunities and barriers to success

This report describes new priorities for carbon-cycle science that complement sustained, ongoing priorities and research. Throughout this Plan, we have also provided suggestions for how to implement these new priorities and integrate them with current research and funding mechanisms. In addition, however, the conduct of science depends on the institutions and institutional structures that support the research, and this brief section provides additional recommendations for institutional structures to improve coordination and to ensure the achievement of the Plan's research recommendations.

- *Provide more opportunities for sustained, long-term funding.* Many aspects of carbon-cycle science cannot be adequately maintained on a three- to five-year funding cycle. As one example, long-term observational efforts of the atmosphere, land, and oceans need funding continuity and certainty. In addition, where new long-term measurement and observational efforts are planned or underway, such as through the NSF National Ecological Observatory Network (NEON) or the Ocean Observatories Initiative (OOI), carbon-cycle scientists should be central to such efforts and able to participate in a sustained fashion.
- *Encourage directed calls for integrated topics in carbon-cycle research*. In addition to regular, disciplinary funding efforts, additional targeted calls to link research in the social, physical, geochemical, and biological sciences could provide a framework for advancing integrative carbon-cycle science. The integrated calls should cover all aspects of research described in this plan that require substantial cross-disciplinary collaboration. As an example calls could be included to explore specific carbon-cycle vulnerabilities in physical systems such as tundra permafrost or in socioeconomic systems that drive carbon-cycle losses (including losses through deforestation). Similarly, a funding call could extend traditional research along biogeochemical environmental gradients to include gradients in socioeconomic factors.
- *Establish stronger links between the Carbon Cycle Interagency Working Group (CCIWG) of the U.S. Global Change Research Program and other U.S. interagency working groups.* Of the ten IWGs, the CCIWG has been particularly active over the past decade. Most of the other nine, including Atmospheric Composition, Ecosystems, Land Use and Land Cover Change, and Observations and Monitoring, have elements with common or interacting components to carbon-cycle research. As a result, increased cooperation among these groups could enhance the success of the new carbon-cycle plan.
- *Develop a strong connection between carbon cycle research and the developing ocean acidification program.* Recent legislation has lead to substantial new investments in ocean acidification (OA) research and the potential development of a national ocean acidification research program. As the OA program develops, it will be important to link the OA efforts with more generalized carbon cycle research to leverage these efforts, and take advantage of potential synergies..
- *Expand the North American Carbon Program to a new Northern Hemisphere Carbon Program*. The North American Carbon Program was established a decade ago to measure and understand the sources and sinks of carbon dioxide, methane, and carbon monoxide in North America and in adjacent ocean regions. To resolve uncertainties in the global carbon sink this decade, a new emphasis is needed on the northern hemisphere *in total*. The expanded emphasis would allow scientists to reconcile observations with model estimates of carbon cycling in the Northern hemisphere.
- *Improve international linkages*. Carbon cycle research requires a global focus that in many cases is best served through collaborative studies with international partners. Although scientists are generally interested in working together with their international colleagues, funding and legal restrictions often make these interactions difficult. The US agencies should explore ways of promoting and facilitating international collaborations.

- *Use the North American Carbon Program and Ocean Carbon and Biogeochemistry program as models to initiate similar, problem-oriented research communities*. The reach of global carbon cycle research is sufficiently interdependent and broad that it is important to achieve interaction, and yet this is difficult to do within specific projects or disciplines. The NACP and OCB have succeeded in establishing on-going dialogue and interaction that has benefited its many diverse constituents. One group with strong roots in both the social and natural sciences is suggested. With guidance from the carbon cycle science community and the research priorities articulated in this Plan, funding agencies should seek to identify opportunities for other large-scale efforts, using NACP and OCB as successful models.
- *Implement a process for periodic measurement and evaluation of progress in pursuing the goals of this Plan.* This Plan should not be perceived as a one-time, static statement. There should be a commitment to periodic (perhaps every 3 years) examination to evaluate the extent to which the goals are being achieved and to ensure that the goals outlined here remain appropriate in a rapidly evolving scientific, environmental, economic, and political environment.
- *Continue to provide broad support for education and training.* The U.S. research agencies have long provided support for education and research involvement by students and early career scientists at all levels and by under-represented groups. We endorse this as a wise investment in the future of our science and strongly encourage continuation.

7.3 Program support

The principal priority detailed in this research Plan is to develop and maintain a broadly-focused, balanced, integrated research agenda. It is clear, however, that the breadth and intensity of the agenda will depend on the resources available. Nonetheless, the interdependence of the many components is critical and the final approach needs to maintain balance within the available resources. Greater commitment of resources will allow more complete understanding sooner. We believe that the importance of carbon cycle research within the pressures of confronting global change call for an accelerated commitment of resources and that the Plan outlined here can be implemented efficiently and effectively.

The current state of carbon cycle science, together with the four research elements identified in Chapter 5, suggests near-term priorities for activities and programs to reach the stated goals. Our ability to reach these goals within the next decade, however, depends strongly on the ability of the US funding agencies to provide full financial support to the research agenda. The 2009 *Our Changing Planet, an annual report to the U.S.* Congress estimated that the total US carbon cycle science budget is currently about $170 million per year (CCSP, 2009). This amount is more than double the funding level at the time that the 1999 Science Plan was published, ignoring inflation, but most of these increases have just come in the past couple of years; the numbers still fall short of the $200-$250M per year budget recommended in the 1999 Science Plan. A summary of the element budgets estimated in Chapter 5 suggests that the total level of support for the new Plan needs to be approximately $500M per year to expand and broaden the scope of carbon-cycle research and to meet all of the stated goals.

Although the importance of understanding the global carbon cycle has been repeated in numerous planning documents and is receiving increased attention from the U.S. Congress, there are many factors that ultimately determine the annual carbon cycle budgets. Evaluating and balancing priorities and determining what is achievable with partial funding is difficult. Here we present three investment scenarios to provide some concept of what might be possible within 10 years with different funding levels. Each scenario is described in terms of its funding for program elements, and its expected outcomes are characterized in terms of meeting the goals of this Plan. Lower levels of funding would limit the range of research activities and/or delay the accomplishment of some of the stated goals.

7.3.1 Scenario I: Full investment in carbon cycle research and observations (~$500M/yr)

Priorities for a full carbon research agenda are described throughout the Plan. Observational networks will be constructed to levels adequate for detecting and attributing change. Data management, synthesis and modeling tools will be developed to take advantage of these observations. A coordinated information service will be developed to provide and disseminate carbon cycle information and products that are easily digestible by the general public, that are delivered in real time in some cases, and that take into account the needs of decision-makers from beginning to end.

Expected outcomes for each of the goals outlined in Chapter 4:

- Goal 1: Full carbon observing networks operating along with a continuity plan for ensuring data quality; Advanced models that include the latest process-based understanding of carbon flux variability; Mechanistic understanding of responses and feedbacks to changing greenhouse gas concentrations and climate based on manipulative experiments.
- Goal 2: The relative importance of various socio-economic processes and their interactions in different parts of the world and at a range of spatial and temporal scales are quantified; The potential range of future emissions from energy and land use are quantified; Studies published showing how carbon prices and other policies affect socio-economic drivers and emissions; Integrated suite of tools, observations, and models available for quantifying and evaluating emissions.
- Goal 3: Vulnerable pools and flows identified and monitored, especially those that may change rapidly in the near future; The physical, chemical, and biological processes important in determining the degree of vulnerability of carbon pools and flows built into diagnostic and mechanistic models; Predictions published on the likelihood, timing and extent of potential changes in vulnerable carbon stocks and flows based on numerical models and empirical methods; Predictions published on the consequences of carbon management and sequestration schemes on vulnerable pools; Carbon management goals supported by scientists helping to prioritize the most vulnerable stocks and flows that require management and the resources that are needed.
- Goal 4: Fully developed research program on the responses of ecosystem productivity, biodiversity, and sustainability to changing levels of carbon dioxide and other greenhouse gases; Published studies on the synergistic effects of rising CO_2 on ecosystems in the presence of altered patterns of climate and associated changes in weather, hydrology, sea level, and ocean circulation; Fully developed, sustained and integrated measurement network for ecosystems in support of scientific research as well as management and decision-making.
- Goal 5: Mechanisms developed for evaluating, integrating and balancing interconnected and potentially competing management goals within the context of carbon cycle science; Published studies on the impacts of carbon management and sequestration strategies on sustainability of ecosystems and ecosystem services, including water resources and biodiversity; The net climate effects of carbon-management pathways, including albedo and other energy-balance components that influence temperature are quantified.
- Goal 6: The fundamental dynamics of decision making as they affect large-scale trends and patterns in carbon stocks and flows are quantified; Decision-maker needs for carbon-cycle-science information are systematically addressed so they can begin to incorporate carbon-related factors into their decision making.

7.3.2 Scenario II: Partial investment in expanded priorities (~$300M/yr)

Priorities for a partial funding of the expanded set of research priorities outlined in this Plan include a limited expansion of existing atmospheric, terrestrial, oceanic and space-based observations, and funding towards integrating social sciences and natural sciences. However, investments in coordination of programs would need to be limited, and fewer opportunities could be created to elucidate the connections between the natural, physical, and social science feedbacks of the carbon cycle. Intensive process studies would be conducted to improve understanding of carbon drivers, but their scope would need to be limited. Development of new tools to model and synthesize the observations and process information would improve the utility of information, but again the scope of these efforts would be limited relative to the recommended funding scenario (Section 7.3.1). Outreach would continue, but coordination between outreach efforts would be limited.

Expected outcomes for each of the goals outlined in Chapter 4:

- Goal 1: A limited expansion of carbon observing networks implemented with a continuity plan for maximizing data quality; Models capable of constraining process-based understanding of carbon flux variability under development; Limited manipulative experiments conducted to provide mechanistic understanding of responses and feedbacks to changing greenhouse gas concentrations and climate.
- Goal 2: Initial studies published on the relative importance of different socio-economic processes; Initial studies published on how carbon prices and other policies affect socio-economic drivers and emissions; The tools, observations, and models needed to quantify and evaluate emissions under development.
- Goal 3: A preliminary listing of the potential magnitude and likelihood of the risk for vulnerable pools and flows; Studies published on the physical, chemical, and biological processes important in determining the degree of vulnerability of carbon pools and flows, but not fully incorporated into models; Carbon management goals supported with publications helping to prioritize the most vulnerable stocks and flows that require management and the resources that are needed.
- Goal 4: Ecosystems at risk from ocean acidification, land-use change, and other carbon-cycle drivers and consequences identified; Extensive studies published on the responses of ecosystem productivity, biodiversity, and sustainability to changing levels of carbon dioxide and other greenhouse gases; Limited enhanced capabilities for sustained and integrated observations of ecosystems in support of scientific research as well as management and decision-making.
- Goal 5: Peer reviewed papers on the likelihood of success and potential for feedback or trade-offs of a few specific proposed carbon-management pathways.
- Goal 6: Decision-maker needs addressed in publications based on available carbon-cycle-science information as decision-makers begin to incorporate carbon-related factors into their work.

Overall, partial funding of the expanded set of priorities outlined in this Plan would result in expanded and improved understanding of the global carbon cycle, but with a coarser resolution, a longer processing time to provide needed information to policy makers, and less integration across various aspects of the carbon cycle.

7.3.3 Scenario III: No increased funding to support expanded priorities (~$200M/yr)

Priorities for a very limited carbon research agenda include little more than maintaining the continuity of existing atmospheric, terrestrial, and oceanic time-series measurements and ongoing model development. Programs with a substantial amount of risk or high costs are unlikely to be funded. There will likely be little improvement in the integrative aspects of carbon cycle research or in the spatial resolution of data products that would provide decision makers with critical information on climate-change.

Expected outcomes for each of the goals outlined in Chapter 4:

- Goal 1: Continue ongoing observations; Maintain current models of process-based understanding of carbon flux variability.
- Goal 2: Begin to develop the tools, observations, and models needed to quantify and evaluate emissions; Physical and social sciences only weakly integrated.

- Goal 3: Publications hypothesizing about vulnerable pools and flows; Studies initiated on the physical, chemical, and biological processes important in determining the degree of vulnerability of carbon pools and flows.
- Goal 4: Identification of primary ecosystems at risk from ocean acidification, land-use change, and other carbon-cycle drivers and consequences; Initial studies published on the responses of ecosystem productivity, biodiversity, and sustainability to changing levels of carbon dioxide and other greenhouse gases.
- Goal 5: Studies published that extrapolate observations to comment on a few specific proposed carbon-management pathways.
- Goal 6: Limited communication with decision-makers as they begin to incorporate carbon-related factors into their decision making.

Under the limited investment scenario, the agencies and carbon cycle community will have to work together to find cost saving opportunities and ways to maximize efficiency in order to address the new components of the Plan.

REFERENCES

Arndt, D. S., M. O. Baringer, M. R. Johnson, 2010: State of the Climate in 2009. Bull. Amer. Meteor. Soc., 91, s1–s222. doi: 10.1175/BAMS-91-7-StateoftheClimate.

Bates, N.R., 2007. Interanual variability of the oceanic CO_2 sink in the subtropical gyre of the North Atlantic Ocean over the last 2 decades. J. Geophys. Res. 112(C9), C09013, doi:10.1029/2006JC003759.

Bates, N. R., J. T. Mathis, and L. W. Cooper, 2009. Ocean acidification and biologically induced seasonality of carbonate mineral saturation states in the western Arctic Ocean, *J. Geophys. Res.*, 114, C11007, doi:10.1029/2008JC004862.

Behrenfeld MJ, O'Malley RT, Siegel DA, McClain CR, Sarmiento JL, et al. 2006. Climate-driven trends in contemporary ocean productivity. Nature 444:752-755

Birdsey, R. et al. 2009. Carbon cycle observations: gaps threaten climate mitigation strategies. Eos 90(34):292, American Geophysical Union.

Brewer, P.G., and E.T. Peltzer 2009 Limits to marine life. Science, 324, 347–348.

Buesseler, K. O., C. H. Lamborg, P. W. Boyd, P. J. Lam, T. W. Trull, R. R. Bidigare, J. K. B. Bishop, K. L. Casciotti, F. Dehairs, M. Elskens, M. Honda, D. M. Karl, D. A. Siegel, M. W. Silver, D. K. Steinberg, J. Valdes, B. Van Mooy, and S. Wilson (2007), Disappearing in the Twilight Zone: Revisiting Carbon Flux Through the Ocean's Twilight Zone, Science, 316(5824), 511c-.

Cai, W-J. 2011. Estuarine and Coastal Ocean Carbon Paradox: CO_2 Sinks or Sites of Terrestrial Carbon Incineration? Annu. Rev. Mar. Sci. 2011. 3:5.1–5.23, doi:10.1146/annurev-marine-120709-142723.

Caldeira, K., and M. E. Wickett, 2005. Ocean model predictions of chemistry changes from carbon dioxide emissions to the atmosphere and ocean. J. Geophys. Res. 110(C9), C09S04, doi:10.1029/2004JC002671.

Cash, D. W., Borck, J. C. & Patt, A. G. 2006. Countering the loading-dock approach to linking science and decision making. Comparative analysis of El Niño/Southern Oscillation (ENSO) Forecasting systems. *Science, Technology and Human Values,* 31**,** 465-494.

Chapin F S III, Randerson J T, McGuire A D, Foley J A and Field C B 2008 Changing feedbacks in the climate–biosphere system *Front. Ecol. Environ.* 6**,** 313–32.

Ciais, P., Dolman, A.J., Dargaville, R., Barrie, L., Bombelli, A., Butler, J., Canadell, P., Moriyama, T. (2010). "GeoCarbon Strategy," Geo Secretariat Geneva,/FAO, Rome, 48 pp.

Climate Change Science Program and Subcommittee on Global Change Research, 2003. Strategic Plan for the U.S. Climate Science Program, Washington D.C., 364 pp.

Climate Change Science Program and Subcommittee on Global Change Research, 2008. Revised Research Plan for the U.S. Climate Change Science Program, Washington D.C., 78 pp.

Cohen, JE (2003) Human population: The next half century. Science 302: 1172-1175.

Cox P.M., Betts R.A., Jones C.D., Spall S.A., Totterdell I.J. (2000) Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. Nature 408:184-187.

DeFries R S, Bounoua L and Collatz G J 2002 Human modification of the landscape and surface climate in the next fifty years. *Global Change Biol.* 8, 438–458.

Denman K.L., Brasseur G., Chidthaisong A., Ciais P., Cox P.M.D., R. E., Hauglustaine D., Heinze C., Holland E., Jacob D., Lohmann U., Ramachandran S., da Silva Dias P.L., Wofsy S.C., Zhang X. (2007) Couplings Between Changes in the Climate System and Biogeochemistry., Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

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.

Dilling, L. (2007) Towards science in support of decision making: characterizing the supply of carbon cycle science. Environmental Science and Policy 10, 48-60.

Dilling, L. and M.C. Lemos. Creating usable science: opportunities and constraints for climate knowledge use and their implications for science policy. Global Environmental Change, in revision

Doney, S.C., R. Anderson, J. Bishop, K. Caldeira, C. Carlson, M._-E. Carr, R. Feely, M. Hood, C. Hopkinson, R. Jahnke, D. Karl, J. Kleypas, C. Lee, R. Letelier, C. McClain, C. Sabine, J. Sarmiento, B. Stephens, and R. Weller., 2004. Ocean carbon and climate change (OCCC): An implementation strategy for U.S. ocean carbon cycle science, university Center for Atmospheric Research, Boulder, CO, 108 pp.

Doney, S.C., V.J. Fabry, R.A. Feely, and J.A. Kleypas, 2009.Ocean acidification: the other CO_2 problem. Annual Review of Marine Science 1: 169-192.

Donner S.D., Kucharik C.J., Foley J.A. (2004) Impact of changing land use practices on nitrate export by the Mississippi River. Global Biogeochemical Cycles [Global Biogeochem. Cycles]. Vol. 18.

Donner, R., S. Barbosa, J. Kurths, and N. Marwan (eds.), 2009.Understanding the Earth as a complex system: Advances in data analysis and modeling in earth sciences. Eur. Phys. J. Special Topics (v. 174).

Duarte C.M., Middelburg J.J., Caraco N. (2005) Major role of marine vegetation on the oceanic carbon cycle. Biogeosciences 2:1-8.

Enting, I.G., 2008. Seeking carbon-consistency in the climate-science-to-policy interface. Biogeochemistry doi: 10.1007/s10533-009-9351-7.

Fabry, V. J., C. Langdon, W.M. Balch, A.G. Dickson, R.A. Feely, B. Hales, D.A. Hutchins, J.A. Kleypas, and C.L. Sabine, 2008. Present and future impacts of ocean acidification on marine ecosystems ande biogeochemical cycles, University of California at San Diego, Scripps Institution of Oceanography, Woods Hole, MA.

Failey, E. and Dilling, L. 2010. Carbon stewardship: Land management decisions and the potential for carbon sequestration in Colorado, USA. Environmental Research Letters, 5 doi:10.1088/1748-9326/5/2/024005

Fargione, J., J. Hill, D. Tilman, S. Polasky, and P. Hawthorne. 2008. Land clearing and the biofuel carbon debt. Science 319:1235–1238.

Field, C., Lobell, D.B., Peters, H.A., Chiariello, N. (2007) Feedbacks of terrestrial ecosystems to climate change. Annual Review of Environment and Resources, 10.1146/annurev.energy.1132.053006.141119.

Friedlingstein P., Cox P., Betts R., Bopp L., von Bloh W., Brovkin V., Cadule P., Doney S., Eby M., Fung I., Bala G., John J., Jones C., Joos F., Kato T., Kawamiya M., Knorr W., Lindsay K., Matthews H.D., Raddatz T., Rayner P., Reick C., Roeckner E., Schnitzler K.-G., Schnur R., Strassmann K., Weaver A.J., Yoshikawa C., Zeng N. (2006) Climate-Carbon Cycle Feedback Analysis: Results from the C4MIP Model Intercomparison. Journal of Climate 19:3337-3353.

GCP, 2010. Global Carbon Project, (at www.globalcarbonproject.org, checked 9 Nov., 2010).

GLP, 2010. Global Land Project, (at www.globalandproject.org, checked 9 Nov., 2010).

Gill, RA, HW Polley, HB Johnson, LJ Anderson, H Maherali, RB Jackson 2002 Nonlinear grassland responses to past and future atmospheric CO_2. Nature 417:279-282.

Houghton, R.A. (2007) Balancing the global carbon budget. Annual Review of Earth and Planetary Sciences 35, 313-347.

IIASA, 2010. Global Energy Assessment, International Institute for Applied Systems Analysis, Laxenburg, Austria (at www.iiasa.ac.at/Research/ENE/GEA/index_gea.html, checked 9 Nov., 2010).

IPCC 2006. 2006 IPCC guidelines for National Greenhouse Gas Inventories. Vol 4. Agriculture, forestry and other land use (AFOLU). Prepared by the National Greenhouse Gas Inventories Programme. Eggleston, H.S., L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Institute for Global Environmental Strategies, Hayama, Japan. Available online at: www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html.

Jackson RB, EG Jobbágy, R Avissar, S Baidya Roy, D Barrett, CW Cook, KA Farley, DC le Maitre, BA McCarl, B Murray 2005 Trading water for carbon with biological carbon sequestration. Science 310:1944-1947.

Jackson, RB, JT Randerson, JG Canadell, RG Anderson, R Avissar, DD Baldocchi, GB Bonan, K Caldeira, NS Diffenbaugh, CB Field, BA Hungate, EG Jobbágy, LM Kueppers, MD Nosetto, DE Pataki. 2008. Protecting climate with forests. Environmental Research Letters 3: 044006, doi:10.1088/1748-9326/3/4/044006.

Jackson RB, J Salzman 2010 Pursuing geoengineering for atmospheric restoration. Issues in Science and Technology 26(4):67-76.

Jet Propulsion Laboratory, 2010a. (at www-airs.jpl.nasa.gov, checked 4 Nov. 2010)

Jet Propulsion Laboratory, 2010b. (at http://tes.jpl.nasa.gov, checked 4 Nov. 2010)

Jones C, J Lowe, S Liddicoat, R Betts12009 Committed terrestrial ecosystem changes due to climate change. Nature Geoscience 2, 484-487.

Körner C 2009 Responses of humid tropical trees to rising CO_2. Annual Review of Ecology, Evolution, and Systematics 40:61-79

Lambin, E.F., et al., “The Causes of Land-Use and Land-Cover Change: Moving Beyond the Myths,” *Global Environmental Change: Human and Policy Dimensions*11, no. 4 (2001): 261–9.

Lemos, M.C. and Morehouse, B.J. (2005) The co-production of science and policy in integrated climate assessments. Global Environmental Change 15, 57-68.

Lowrey, J., Ray, A. and Webb R. (2009) Factors influencing the use of climate information by Colorado municipal water managers. Climate Research 40, 103-119.

Millennium Ecosystem Assessment (MA), *Ecosystems and Human Well-being: A Framework for Assessment* (Island Press, 2003)

Millennium Ecosystem Assessment (MA), *Ecosystems and Human Well-being: A Framework for Assessment* (Island Press, 2003)

Morgan, M.G., H. Dowlatabadi, M. Henrion, D. Keith, R. Lempert, S. McBride, M. Small. T. Wilbanks, 2009. Best practice approaches for characterizing, communicating, and incorporating scientific uncertainty in climate decision making, Synthesis and Assessment Product 5.2 Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research,. National Oceanic and Atmospheric Administration, Washington D.C., 96 pp.

Moser, S. and L. Dilling, Eds. 2007. Creating a Climate for Change: Communicating Climate Change—Facilitating Social Change. Cambridge University Press, Cambridge UK.

Moss, R., Wilhelmi, O., Downton, M., and Gruntfest, E. (2005). Lessons from an interdisciplinary project. Bull. Am. Met. Soc. DOI: 10.1175/BAMS-86-11-1593.

NACP, 2010a. North American Carbon Program (at www.nacarbon.org/nacp/index.html,)

NACP, 2010b, Modeling and Synthesis Thematic Data Center (MAST-DC), (at http://nacp.ornl.gov/ checked 4 Nov. 2010)

National Research Council, 2007. Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond, The National Academies Press, Washington D.C., 456 pp.

National Research Council, 2007. Evaluating Progress of the U.S. Climate Change Science Program: Methods and Preliminary Results, The National Academy Press, Washington D.C. 170 pp.

National Research Council, 2010a. Advancing the Science of Climate Change, The National Academies Press, Washington D.C., 506 pp.

National Research Council, 2010b. Limiting the magnitude of future climate change, The National Academies Press, Washington D.C., 258 pp.

National Research Council, 2010c. Adapting to the Impacts of Climate Change. The National Academies Press, 325pp.

NEON, 2010. (at www.neoninc.org checked 4 Nov. 2010) National Ecological Observatory Inc.

NIES, 2010. The Greenhouse Gas Observing Satellite (at www.gosat.nies.go.jp/index_e.html checked 4 Nov. 2010), National Institute for Environmental Studies, Japan.

NOAA, 2010. (at www.nodc.noaa.gov checked 4 Nov. 2010) National Oceanic and Atmospheric Administration.

North American Carbon Program Science Plan 2002 A plan for carbon cycle research focused on measuring and understanding sources and sinks of CO_2, CH_4, and CO in North America and adjacent oceans.

NRC: Committee on Strategic Advice on the U.S. Climate Change Science Program 2009 Restructuring Federal Climate Research to Meet the Challenges of Climate Change. National Academies Press, Washington, D.C.

NRC: Panel on Strategies and Methods for Climate-Related Decision Support; National Research Council 2009 Informing Decisions in a Changing Climate. National Academies Press, Washington, D.C.

NRC: Committee on the Development of an Integrated Science Strategy for Ocean Acidification Monitoring, Research, and Impacts Assessment; National Research Council 2010d Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean. National Academies Press, Washington, D.C.

ORNL, 2010. Ameriflux (at http://public.ornl.gov/ameriflux, checked 4 Nov. 2010), Oak Ridge National Laboratory.

Page SE, Siegert F, Rieley JO, Boehm H-DV, Jaya A Limin S 2002 The amount of carbon released from peat and forest fires in Indonesia during 1997. Nature 420:61-65.

Piñeiro, G, EG Jobbágy, J Baker, BC Murray, RB Jackson 2009 Set-asides can be better climate investment than corn-ethanol. Ecological Applications 19:277-282.

Pörtner, H. 2008 Ecosystem effects of ocean acidification in times of ocean warming: a physiologist's view. Mar. Ecol. Prog. Ser., 373, 203–217.

Qian, H.-F., R. Joseph, N. Zeng, 2010: Enhanced terrestrial carbon uptake in the northern high latitudes in the 21st century from the C4MIP model projections. Global Change Biology ,DOI: 10.1111/j.1365-2486.2009.01989.

Raupach, M. et al., 2007, Global and regional drivers of accelerating CO2 emissions, PNAS 104: 10288–10293.

Richards K R, Sampson R N, Brown S. 2006 Agricultural and forestlands: US carbon Policy Strategies A report prepared for the Pew Center on Global Climate Change. Available online at: http://www.pewclimate.org/reports/All (Last accessed March 15, 2010).

Riebesell U. (2008) Climate change: Acid test for marine biodiversity. Nature 454:46-47.

Root, T.L., Price, J.T., Hall, K., Schneider, S.H., Rosenzweig, C., Pounds, J.A. (2004) Fingerprints of global warming on wild animals and plants. Nature 421, 57-60.

Rosenzweig, C., Karoly, D., Vicarelli, M., Neofotis, P., Wu, Q., Casassa, G., Menzel, A., Root, T.L., Estrella, N., Seguin, B., Tryjanowski, P., Liu, C., Rawlins, S., Imeson, A. (2008) Attributing physical and biological impacts to anthropogenic climate change. Nature 453, 353-358.

Sarmiento, J.L. and S.C. Wofsy. 1999. A U.S. carbon cycle science plan. Report of the Carbon and Climate Working Group for the U.S. Global Change Research Program. Washington, DC: U.S. Global Change Research Program.

Schimel D.S., House J.I., Hibbard K.A., Bousquet P., Ciais P., Peylin P., Braswell B.H., Apps M.J., Baker D., Bondeau A., Canadell J., Churkina G., Cramer W., Denning A.S., Field C.B., Friedlingstein P., Goodale C., Heimann M., Houghton R.A., Melillo J.M., Moore B., Murdiyarso D., Noble I., Pacala S.W., Prentice I.C., Raupach M.R., Rayner P.J., Scholes R.J., Steffen W.L., Wirth C. (2001) Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems. Nature 414:169-172.

Schneider, S.H., S. Semenov, A. Patwardhan, I. Burton, C.H.D. Magadza, M. Oppenheimer, A.B. Pittock, A. Rahman, J.B. Smith, A. Suarez and F. Yamin, 2007: Assessing key vulnerabilities and the risk from climate change. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 779-810.

Schuur EAG, James Bockheim, Josep G. Canadell, Eugenie Euskirchen, Christopher B. Field, Sergey V. Goryachkin, Stefan Hagemann, Peter Kuhry, Peter M. Lafleur, Hanna Lee, Galina Mazhitova, Frederick E. Nelson, Annette Rinke, Vladimir E. Romanovsky, Nikolay Shiklomanov, Charles Tarnocai, Sergey Venevsky, Jason G. Vogel, and Sergei A. Zimov 2008 Vulnerability of Permafrost Carbon to Climate Change: Implications for the Global Carbon Cycle, BioScience 58(8):701-714. 2008, doi: 10.1641/B580807.

Searchinger, T., R. Heimlich, R. A. Houghton, F. Dong, A., Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T.-H. Yu. 2008. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. Science 319: 1238–1240.

Shepherd, J. *et al*. 2009 *Geoengineering the Climate: Science, Governance and Uncertainty* (London, UK: Royal Society,Royal Society Working Group on Geoengineering.

SOCCR, 2007. The first State of the Climate Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle, eds. A. W. King, L. Dilling, G.P. Zimmerman, D.M. Fairman, R.A. Houghton, G. Marland, A.Z. Rose, and T.J. Wilbanks, Climate Change Science Program and Subcommittee on Global Change Research, National Ocean and Atmospheric Administration, Asheville, NC, 242 pp.

Stern, P.C. 2002. Human interactions with the carbon cycle: summary of a workshop. Committee on the Human Dimensions of Global Change. Washington, DC: National Academy Press.

Taleb, N.N., 2007. The Black Swan: The impact of the highly improbable. Random House, N.Y., N.Y.

Tans, P., 2010. Mauna Loa CO2 Data, US National Oceanic and Atmospheric Administration, Earth System Research Laboratory, (at www.esrl.noaa.gov/gmd/ccgg/trends/, checked 4 Nov. 2010).

Tschakert, Petra, Elisabeth Huber-Sannwald, Dennis S. Ojima, Michael R. Raupach, and Erich Schienke. 2008. Principles for holistic, adaptive management of the terrestrial carbon cycle at local and regional scales, through multi-criteria analysis. Global Environmental Change 18: 128–141

Turner W.R., Oppenheimer M., Wilcove D.S. (2009) A force to fight global warming. Nature 462:278-279.

UGEC, 2010. Urbanization and Global Environmental Change, (At www.ugec2010.org, checked 9 Nov., 2010).

USDA, Forest Service, 2010. (at http://fia.fs.fed.us/, checked 4 Nov. 2010), U.S. Department of Agriculture, Forest Service.

US DOE, 2007. Scenarios of greenhouse gas emissions and atmospheric concentrations(Part A) and review of integrated scenario development and application (Part B). A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research (Clarke, L., J. Edmonds, J. Jacoby, H. Pitcher, J. Reilly, R. Richels, E. Parson, V. Burkett, K. Fisher-Vanden, D. Keith, L. Mearns, C. Rosenzweig, and M. Webster (authors)), U.S. Department of Energy, Office of Biological and Environmental Research, Washington DC, 260 pp.

U.S. Global Change Research Program (1989) Our Changing Planet: A U.S. Strategy for Global Change Research, Washington, D.C., 38 pp.

U.S. Global Change Research Program, 2009. Our Changing Planet, A report by the U.S. Global Change Research Program and the Subcommittee on Global Change Research: A supplement to the President's budget for fiscal year 2010, USGCRP, Washington D.C., 172pp.

U.S. Global Change Research Program 2009 *Global Climate Change Impacts in the United States.*

Walter, K. M. , S. Zimov, J.P. Chanton, D. Verbyla, F.S. Chapin III (2006), Methane Bubbling from Siberian Thaw Lakes as a Positive Feedback to Climate Warming, Nature, 443, 71-75.

Waycott, M., C. M. Duarte, T. J. B. Carruthers, R. J. Orth, W. C. Dennison, S. Olyarnik, A. Calladine, J. W. Fourqurean, K. L. Heck, A. R. Hughes, G. A. Kendrick, W. J. Kenworthy, F. Short, T. , and S. L. Williams (2009), Accelerating loss of seagrasses across the globe threatens coastal ecosystems, Proceedings of the National Academy of Sciences of the United States of America, 106(30), 12377-12381.

Williams, J.W., Jackson, S.T., Kutzbach, J.E. (2007) Projected disturbances of novel and disappearing climates by 2100. Proceedings of the National Academy of Sciences 104, 5738-5742.

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

APPENDIX A: Charge to the Co-Leads of the Carbon Cycle Science Working Group, and Overview of the Carbon Cycle Interagency Working Group

A.1 Charge to the co-leads of the Carbon Cycle Science Working Group

A New U.S. Carbon Cycle Science Plan

(CCIWG Approved 18 May 2008)

Rationale: *A U.S. Carbon Cycle Science Plan* (Sarmiento and Wofsy, 1999) was developed in 1998, published in 1999, and is now essentially 10 years old. Much has been learned and there is no doubt much yet to be done, but it is time to take a fresh look at the scientific questions and priorities detailed in that report. It is important to note that this plan, produced by the scientific community, was the single most important and influential input into the Carbon Cycle chapter of the 2003 *Strategic Plan for the U.S. Climate Change Science Program*.

The U.S. Climate Change Science Program (CCSP) is now working on a minor update of its 2003 Strategic Plan and intends to draft a major revision in 2009. CCSP leaders have asked the Carbon Cycle Interagency Working Group (CCIWG) to identify by December 2008 the "building blocks" it will use to develop its contribution to the revised strategic plan. The CCIWG would again like to have an up-to-date report from the scientific community on the most important scientific challenges and priorities for U.S. carbon cycle research as the major "building block" to draw upon in drafting its inputs for the new strategic plan. If initiated immediately, there would be time to complete a community-based study similar to the one produced by the Carbon and Climate Working Group led by Jorge Sarmiento and Steve Wofsy in 1998-1999.

Immediate Actions to Initiate Planning: The CCIWG should consult with its Carbon Cycle Science Steering Group (CCSSG) to request their assistance in defining and organizing the community-based planning activity needed to develop the new report. It does not seem reasonable to charge the CCSSG with developing the report itself (although individual members may wish to participate), but rather they should help to define the process and identify the working group participants. It would be reasonable to make the new working group a subcommittee of the CCSSG, if the CCSSG agrees. The working group will need to develop a work plan and cost plan that can guide their activities and schedule and serve to justify the resources to be provided through the CCIWG agencies. The working group will be responsible for end-to-end implementation of the planning process, but it is anticipated that some of the authors for the final report, perhaps even the lead authors or editors, may emerge through leadership roles assumed by other community members as the planning proceeds. Working group members should represent the composition of the community as well as possible and include active researchers likely to be engaged in the next 10 years of carbon cycle research.

Charge to the New Working Group: The carbon cycle science working group will be responsible for developing an updated, revised, or new science plan for U.S. carbon cycle science, identifying challenges and priorities for the next decade (~2010-2020) and involving the broader community. The group will:

- Define a process that reaches out to and engages the U.S. carbon cycle science community at key stages (for example, one or more community workshops and inviting many to participate in a peer review of the report), but that is no more elaborate and lengthy than is needed to do the job.
- Consider how to engage other key stakeholders to ensure that their interests and priorities are taken into account – especially key decision-support needs.

- Develop a schedule that as much as possible matches CCSP planning needs (for example, to have preliminary findings available as near to December 2008 as possible and final publication of the report before content is fixed for the next strategic plan for the U.S. CCSP)
- Prepare a work plan and cost plan for the planning activities and report preparation and submit this to the CCIWG agencies for internal review, approval and funding.
- Implement the planning process, holding whatever meetings and workshops are included in the approved work plan, to identify the most important science issues for the U.S. to pursue and what is needed to address them. The following should be taken into consideration (the order below is not a prioritization):
    - The most important, exciting, challenging science questions that are ripe for new investment.
    - The U.S. Government's need for prioritized research to address critical uncertainties regarding global climate change.
    - The most important observations and research infrastructure in need of continuing, stable support.
    - The needs of policy makers and resources managers for decision support related to carbon management, climate change mitigation (including emissions reduction and carbon sequestration) and/or adaptation.
    - The previous (1999) report on U.S. carbon cycle science – what is no longer important, what needs only updating, what requires major revision, what needs to be added? Use it as a starting point, if possible, but if something wholly new would be best, that would be acceptable.
    - Existing carbon cycle science budget levels and anticipated future funding levels; recommended activities and priorities should either be more or less affordable within existing budgets or tied to well-defined initiatives that could be proposed with high priority for new funding (Note: both should be included!)
    - The missions/goals of the U.S. agencies that conduct carbon cycle science and the relevant scientific and/or operational infrastructure that they are mandated to support.
    - International programs, plans, priorities for carbon cycle science
- Write and publish a report on the findings of the working group.
    - Select the editor(s) for the report (suggest co-editors to cover the span of "disciplinary expertise needed – at least land-ocean, perhaps land-atmosphere-ocean?), subject to the concurrence of the CCSSG Chair and the CCIWG.
    - Recruit additional authors outside of the working group, as needed.
    - Keep the CCIWG apprised of findings and status of the report and seek their comments/inputs at an appropriate time(s)
    - Make a mature draft of the report available for community review and comment, and revise the draft to appropriately respond to this review
    - Arrange for the final report to be made available (help with electronic posting and/or printing could be arranged through the Carbon Cycle Science Program Office and UCAR)

A.2 Carbon Cycle Interagency Working Group

The Carbon Cycle Interagency Working Group was established under the U.S. Climate Change Science Program to promote interagency cooperation and coordination, help secure funding, prepare individual and joint agency initiatives and solicitations, and involve the scientific community with the purpose of providing the needed science to understand the carbon cycle. CCIWG members represent 12 federal agencies.

- Department of Agriculture

    - Agricultural Research Service
    - Economic Research Service
    - Forest Service
    - National Institute of Food and Agriculture
    - Natural Resource Conservation Service
- Department of Energy
- Environmental Protection Agency
- National Aeronautics and Space Administration
- National Institute of Standards and Technology
- National Oceanic and Atmospheric Administration, Department of Commerce
- National Science Foundation
- US Geological Survey, Department of the Interior

APPENDIX B: Carbon Cycle Science Working Group Membership

Bob Anderson
Lamont-Doherty Earth Observatory
Earth and Environmental Sciences
The Earth Institute
Columbia University

Deborah Bronk
Department of Physical Sciences
Virginia Institute of Marine Sciences
College of William & Mary

Ken Davis
Department of Meteorology
Pennsylvania State University

Ruth DeFries
Department of Ecology, Evolution, and Environmental Biology
Columbia University

Scott Denning
Department of Atmospheric Science
Colorado State University

Lisa Dilling
Center for Science and Technology Policy Research
Cooperative Institute for Research in Environmental Sciences
University of Colorado, Boulder

Rob Jackson – Co-lead
Department of Biology
Nicholas School of the Environment
Duke University

Andy Jacobson
NOAA Earth System Research Laboratory, Global Monitoring Division
University of Colorado, Cooperative Institute for Research in Environmental Sciences

Steve Lohrenz
Department of Marine Science
University of Southern Mississippi

Gregg Marland – Co-lead
Ecosystem Simulation Science Group, Environmental Sciences Division
Oak Ridge National Laboratory

David McGuire
Alaska Cooperative Fish and Wildlife Research Unit
U.S. Geological Survey
Institute of Arctic Biology
Department of Biology and Wildlife
University of Alaska

Galen McKinley
Department of Atmospheric and Oceanic Sciences
University of Wisconsin, Madison

Anna M. Michalak – Co-lead
Department of Civil and Environmental Engineering
Department of Atmospheric, Oceanic, and Space Sciences
University of Michigan

Charles Miller
Jet Propulsion Laboratory
California Institute of Technology

Berrien Moore
College of Atmospheric and Geographic Sciences
University of Oklahoma

Dennis Ojima
Natural Resource Ecology Laboratory
Colorado State University
Heinz Center

Brian O'Neill
Integrated Assessment Modeling, Climate Change Research
National Center for Atmospheric Research

Jim Randerson
Department of Earth System Science
University of California, Irvine

Steve Running
Numerical Terradynamic Simulation Group
College of Forestry and Conservation
University of Montana

Christopher Sabine – Co-lead
Ocean Climate Research Division
NOAA Pacific Marine Environmental Laboratory

Brent Sohngen
Department of Agricultural, Environmental, and Development Economics
Ohio State University

Pieter Tans
Climate Monitoring and Diagnostics Laboratory
NOAA Earth System Research Laboratory

Peter Thornton
Environmental Simulation Science Group
Oak Ridge National Laboratory

Steve Wofsy
School of Engineering and Applied Sciences
Harvard Forest
Harvard University

Ning Zeng
Department of Atmospheric and Oceanic Science
University of Maryland

APPENDIX C: Outreach Activities

The following is a list of meetings, workshops, conferences, and publications where information about the new U.S. Carbon Cycle Science Plan has been presented and discussed:

November 17-18, 2008	Carbon Cycle Science Working Group (CCS WG) Meeting Washington, DC Scope: Dedicated workshop
December 9-10, 2008	Carbon Cycle Science Steering Group (CCSSG) Meeting Washington, DC Scope: Report on CCS WG meeting and presentation
February 17-20, 2009	North American Carbon Program (NACP) All Investigators' Meeting San Diego, CA Scope: CCS WG side meeting, plenary presentation, dedicated breakout session
March 24, 2009	"A U.S. carbon cycle science plan: First meeting of the Carbon Cycle Science Working Group; Washington, D.C., 17-18 November 2008" by A.M Michalak, R. Jackson, G. Marland, and C. Sabine, published in EOS, Transactions of the American Geophysical Union, 90(12), p. 102-103.
March 27, 2009	CCS WG Scoping Paper published online at http://www.carboncyclescience.gov/carbonplanning.php
May 24-27, 2009	2009 Joint Assembly, The Meeting of the Americas Toronto, Ontario, Canada Scope: Presentation
June 1-2, 2009	CCS WG Meeting Washington, DC Scope: Dedicated workshop
June 3-4, 2009	CCSSG Meeting Washington, DC Scope: Report on CCS WG meeting and presentation
June 23-25, 2009	Earth System Science Partnership (ESSP) Global Carbon Project (GCP) Science Steering Committee (SSC) Beijing ,China Scope: Progress report and presentation
July 20-23, 2009	Ocean Carbon and Biogeochemistry (OCB) Summer Workshop Woods Hole, MA Scope: Presentations and panel discussion
August 2-7, 2009	94th Ecological Society of America Meeting Albuquerque, NM Scope: Presentation
September 13-19, 2009	8th International Carbon Dioxide Conference Jena, Germany Scope: Abstract and poster presentation
September 21-25, 2009	OceanObs'09 Venice-Lido, Italy Scope: Presentation and poster
September 21-23, 2009	AmeriFlux Meeting Washington, DC Scope: Presentation

September 30, 2009	NACP Science Steering Group (NACP SSG) Washington, DC Scope: Presentation
November 6, 2009	CCSWG. Recommendations Summary White Paper published online at http://www.carboncyclescience.gov/carbonplanning.php
November 19-20, 2009	39th National Research Council (NRC) Committee on Human Dimensions of Global Change Meeting Washington, DC Scope: Presentation
December 3-4, 2009	CCSSG Meeting Washington, DC Scope: Progress report and presentation
December 14-18, 2009	American Geophysical Union (AGU) Fall Meeting San Francisco, CA Scope: Town hall meeting
March 12-13, 2010	Human Dimensions Workshop Washington, DC Scope: Dedicated workshop
June 15-17, 2010	ESSP GCP SSC Meeting Norwich, United Kingdom Scope: Progress report and discussion
July 13-14, 2010	NASA Carbon Monitoring System Scoping Workshop Boulder, CO Scope: Presentation and discussion
July 19-22, 2010	OCB Summer Workshop San Diego, CA Scope: Presentation and discussion
August 23-24, 2010	CCS WG Workshop Boulder, CO Scope: Dedicated workshop

APPENDIX D: List of Acronyms

ACE - Aerosol – Cloud - Ecosystems

AIRS – Atmospheric Infrared Sounder

ALOS - Advanced Land Observing Satellite

AmeriFlux – Tower network that provides continuous observations of ecosystem level exchanges of CO_2, water, energy and momentum, composed of sites from North, South, and Central America.

ASCENDS – Active Sensing of CO2 Emissions over Nights, Days, and Seasons

CCIWG – Carbon Cycle Interagency Working Group

CCSP – Climate Change Science Program

CH_4 – Methane

CO_2 – Carbon dioxide

DESDynI - Deformation, Ecosystem Structure and Dynamics of Ice (), the

DOE – Department of Energy

EOS – Earth Observing System

ESRL – Earth System Research Laboratory

FACE – Free Air CO_2 Enrichment

FIA – Forest Inventory and Analysis

FLUXNET - Global network of micrometeorological tower sites that use eddy covariance methods to measure the exchanges of CO_2, water vapor, and energy between terrestrial ecosystems and the atmosphere.

GCP – Global Carbon Project

GEO-CAPE - Geostationary Coastal and Air Pollution Events

GHG – Greenhouse Gas

GOSAT – Greenhouse Gas Observing Satellite

HyspIRI - Hyperspectral Infrared Imager

ICESat-2 - Ice, Cloud,and land Elevation Satellite-2

IMBER – Integrated Marine Biogeochemistry and Ecosystem Research

IPCC – Intergovernmental Panel on Climate Change

JPSS – Joint Polar Satellite System

LDCM - Landsat Data Continuity Mission

LIST - Lidar Surface Topography

LUCC – Land Use and Cover Change

MAST-DC – Modeling and Synthesis Thematic Data Center

NACP – North American Carbon Program

NASA – National Aeronautics and Space Administration

NEON – National Ecological Observatory Network

NIES – National Institute for Environmental Studies

NOAA – National Oceanic and Atmospheric Administration

NPOESS - National Polar-orbiting Operational Environmental Satellite System

NPP - NPOESS Preparatory Project

NRC – National Research Council

NSF – National Science Foundation

OA – Ocean Acidification

OCB – Ocean Carbon and Biogeochemistry

OCB-SSG – Ocean Carbon and Biogeochemistry Scientific Steering Group

OCCC – Ocean Carbon and Climate Change

OCCC-SSG – Ocean Carbon and Climate Change Scientific Steering Group

OCO – Orbiting Carbon Observatory

OCO-2 – Orbiting Carbon Observatory 2

OOI – Ocean Observatories Initiative

ORNL – Oak Ridge National Laboratory

PALSAR - Phased Array type L-band Synthetic Aperture Radar

RCP – Representative Concentration Pathway

REDD – Reducing Emissions from Deforestation and Degradation

SCLP - Snow and Cold Land Processes

SeaWiFS – Sea-viewing Wide Field-of-view Sensor

SMAP - Soil Moisture Active and Passive

SOCCR – State of the Carbon Cycle Report

SOLAS – Surface Ocean Lower Atmosphere Study

TES – Tropospheric Emission Spectrometer

UGEC – Urban and Global Environmental Change

USDA – U.S. Department of Agriculture

USGCRP – U.S. Global Change Research Program

VIIRS - Visible Infrared Imager Radiometer Suite

VOS – Volunteer Observing Ships

WOCE/JGOFS – World Ocean Circulation Experiment/Joint Global Ocean Flux Study

APPENDIX E: Acknowledgments

This document represents the diverse contributions of a large number of people. This effort was led by a working group made up of 25 members, of whom all have contributed ideas and many have contributed text. Nonetheless, the 4 co-chairs have tried to organize, synthesize, summarize, and approach consensus and they accept primary responsibility for the final tone and content of this document. The intent from the beginning has been to produce a research agenda that truly represents a consensus view of the active research community and we are grateful for the number of committee members from all disciplines who have contributed generously of their time and ideas. Through many presentations and other exposures to the scientific community at large we have received a great deal of additional input, including valuable discussions that helped to shape the plan and determine the breadth and balance contained within. We are grateful for the wisdom and concerns shared by so many of our friends and colleagues.

It is impossible to adequately acknowledge the magnitude of the contributions from committee members (listed in Appendix B) or from those colleagues who are represented in this document only by their ideas, but there are three additional groups/individuals with whom we owe a special debt.

In addition to their financial support, the members of the Carbon Cycle Interagency Working Group have been remarkably generous with their ideas, insights, and patience and we are grateful; our commitments of time and energy to this effort could not have gone forward without the support of our home institutions; Roger Hanson (Director of the U.S. Carbon Cycle Science Program office) has been with us every step of way with support and wisdom on everything from history, context, intellectual content, and hotel and restaurant arrangements. Thanks to all!