Chapter 1: Introduction

Rationale

Future concentrations of atmospheric carbon dioxide (CO_2) must be known to characterize and predict the behavior of the Earth's climate system on decadal to centennial time scales. Predicting these future CO_2 concentrations in turn requires understanding how the global carbon cycle has functioned in the past and how it functions today. For these reasons,a variety of federal agencies have funded scientific research into the oceanic, atmospheric,and terrestrial components of the global carbon cycle. This research has been an important element of the U.S.Global Change Research Program (USGCRP) since its inception.The carbon cycle consists of an integrated set of processes affecting closely coupled carbon reservoirs in the atmosphere and ocean and on land. Successful predictions require considering all the important processes that affect these reservoirs. Programs must therefore support a well-integrated approach,with links fostered among atmospheric,oceanic,terrestrial,and human sciences.

Recently, interest in the global carbon cycle has intensified. Progress in scientific understanding and technology has given rise to new scientific opportunities to address critical components of the atmosphere-ocean-land system. Policy makers have also been seeking the appropriate responses to the United Nations Framework Convention on Climate Change and to the underlying societal and scientific concerns. There is particular impetus to understand the sources and sinks of carbon on continental and regional scales and the development of these sources and sinks over time. Also critical is elucidating how ocean carbon uptake and marine and terrestrial ecosystems might respond to changing climate and ocean circulation,or to the enhanced availability of CO_2 and fixed nitrogen compounds associated with human activities such as the burning of fossil fuels. Changes in ecosystems may affect climate and may have important resource and societal implications. Another topic of increasing interest is the purposeful sequestration,or storage,of carbon by burial below ground or in the ocean,or by land management practices,to keep some amount of carbon from entering the atmosphere in the form of CO_2.

The ultimate measure of the success of the carbon cycle research program will be its ability to provide pragmatic answers to both scientific and societal questions. Scientists and policy makers must be able to evaluate alternative scenarios for future emissions from fossil fuels,effects of human land use,sequestration by carbon sinks,and responses of carbon cycling to potential climate change.

This document outlines a U.S.Carbon Cycle Science Plan (CCSP) with the view that ***credible predictions of future atmospheric carbon dioxide levels can be made given realistic emission and climate scenarios that incorporate relevant interactions and feedbacks.***

The problems of understanding the carbon cycle and improving related predictive capabilities are complex. These problems require coordinated interdisciplinary research that is scientifically rigorous and that at the same time advances knowledge and serves societal needs. Achieving all this together is clearly a challenge. The present plan aims at specifying an optimal mix of sustained observations,modeling,and innovative process studies and manipulative experiments such that the whole is greater than the sum of parts. This strategy for an integrated CCSP has two basic thrusts:

- Developing a small number of new research initiatives that are feasible,cost-effective,and compelling,to address difficult,linked scientific problems
- Strengthening the broad research agendas of the agencies through better coordination, focus,conceptual and strategic framework,and articulation of goals.

In sum,the rationale for a CCSP is severalfold. Future concentrations of atmospheric CO_2 must be projected to characterize and predict the behavior of the Earth's climate system on decadal to centennial time scales. Moreover, the scientific community is in a good position to make important progress in this area. But making such progress will require an unprecedented level of coordination among the scientists and government agencies that support this research.

Outline of the Research Program

The CCSP is designed to address two basic questions:

1. What has happened to the CO_2 that has already been emitted through human activities (anthropogenic carbon dioxide)?
2. What will be the future atmospheric carbon dioxide concentrations resulting from both past and future emissions?

The first of these questions concerns the history and the present behavior of the carbon cycle. Information about the past and present provides us with the most powerful clues for understanding the behavior of anthropogenic CO_2 and the processes that control it,as well as its sensitivity to perturbations. Achieving a better understanding of these phenomena will require a sustained observational effort.

The second question directly concerns the goal of predictability. The CCSP will study the essential processes that influence how carbon cycling may change in the future. These studies will be integrated in a rigorous and comprehensive effort to build and test models of carbon cycle change,to evaluate and communicate uncertainties in alternative model simulations,and to make these simulations available for public scrutiny and application.

The long-term goals and implementation objectives that flow from the two questions above are shown in Table 1.1 and reviewed in the sections that follow below on sustained observations,manipulative experiments,and model development.

In addition to the physical,biogeochemical,and ecological processes that are traditionally studied in carbon cycle research,the integrated CCSP must address human influences as well,with special emphasis on understanding the consequences of land use and land cover changes;the effects of various management strategies,such as no-till agriculture, long- vs short-rotation forestry, and deep ocean CO_2 injection; and the effectiveness of response/mitigation options such as controlling carbon emissions or enhancing carbon sinks. The CCSP addresses the interactions between human systems and the carbon cycle in much the same way that it does interactions between the climate system and the carbon cycle. While the program does not encompass either broad socioeconomic research or climate research, it does consider problems of the interactions of human systems and climate with the carbon cycle.

Sustained Observations

A program of sustained observations of sufficient spatial and temporal resolution is essential for determining interannual variability and long-term trends in terrestrial and oceanic carbon sources and sinks,both globally and regionally. Such a program is also required to monitor the effectiveness and stability of any purposeful carbon sequestration activities,as well as to detect major shifts in

Table 1.1 US Carbon Cycle Science Plan

Scientific Question	Long-Term Goals	Implementation Objectives
What has happened to the carbon dioxide already emitted by human activities (anthropogenic CO_2) including that emitted through combustion of fossil fuels, deforestation, and agriculture?	• Improve quantitative characterization of past and present sources and sinks for CO_2 • Understand mechanisms over the full range of relevant time scales • Improve understanding of the sinks (ocean and land) for anthropogenic CO_2	Develop sustained observational efforts to: • Accurately measure major net fluxes of CO_2 from terrestrial and oceanic regions of the world • Quantitatively determine the processes (long-term transient) that control net sequestration of anthropogenic CO_2 and the temporal and spatial distribution of such sequestration • Monitor the efficacy and stability of purposeful carbon sequestration activities • Provide early detection of major shifts in carbon cycle function that may lead to rapid release of CO_2
What will be the future atmospheric carbon dioxide concentrations resulting from both past and future emissions?	• Provide predictions of future sources and sinks (ocean and land) with enhanced credibility using models and experiments incorporating the most important mechanisms • Provide a scientific basis to evaluate carbon sequestration strategies and measure net CO_2 emissions from major regions of the world	• Provide a framework for rigorous, independent intercomparison and evaluation of climate and carbon models using comprehensive data developed in the Carbon Cycle Science Program and both formal and informal model assessment activities • Develop models of the carbon cycle in the atmosphere and ocean and on land to— - Predict the lifetime, sustainability, and interannual/decadal variability of terrestrial and ocean sinks - Predict how changes in human activities and the climate system will affect the global carbon cycle - Evaluate potential management strategies to enhance carbon sequestration • Evaluate measurement strategies for detecting emissions from major regions of the world

the functioning of the carbon system that might lead to major changes in atmospheric CO_2.

Data on global and regional variability and trends in CO_2 concentrations provide us with the most valuable information on the response of the global carbon cycle to climate changes and to processes such as forest regrowth or fertilization owing to increased CO_2 and nitrogen oxides (NO_x) from fossil fuels. Monitoring programs should take advantage of the recent insights from inverse models to combine limited direct observations with model estimates to determine the spatial and temporal distribution of carbon sources and sinks. The program of observations must also include a strong focus on understanding critical processes that determine the long-term sequestration of anthropogenic CO_2, as well as its interannual variability.

The Mauna Loa and South Pole CO_2 time series of C. D. Keeling provided the first unambiguous evidence of increasing atmospheric CO_2. Time series data for CO_2, combined with tracers, constituents of the atmosphere that have a specific origin or change in an understood way, such as $^{14}CO_2$, $^{13}CO_2$, and O_2, provide strong quantitative constraints which help confirm the factors regulating the global balance of carbon. Expanded atmospheric observation networks, including airborne measurements and a growing number of flux towers, which measure the amount of CO_2 going into or out of a certain area of land over a period of time, have enabled scientists to begin defining the regional distribution of carbon sources and sinks. This work is still rudimentary, but already indicates great potential for assessing source and sink distributions at smaller (e.g., regional) scales. ***A major hypothesis issuing from the past decade of research is that there exists a large terrestrial sink for anthropogenic CO_2 in the Northern Hemisphere. Much of the near-term observational work proposed in this plan aims to test this hypothesis.***

A critical task is to improve the modeling and statistical tools needed to infer sources and sinks and to otherwise interpret these observations. Additional oceanic and terrestrial observations must also be defined to complement global monitoring data so that better temporal and spatial resolution is achieved. Such observations should improve understanding of seasonal and year-to-year variability, and they should monitor regions identified as significant sources and/or sinks.

Three areas in particular—areas that the scientific community is positioned to address—require near-term emphasis:

- **Establishing accurate estimates of the magnitude and partitioning of the current Northern Hemisphere terrestrial carbon sink.**
- **Establishing accurate estimates of the oceanic carbon sink, including its interannual variability and spatial distribution. In the near-term, attention should be directed to the North Atlantic and North Pacific, to complement and optimize use of the terrestrial data on the Northern Hemisphere. In the long-term, emphasis should turn to the Southern Hemisphere oceans poleward of approximately 30°S.**
- **Establishing accurate estimates of the impact on the evolving carbon budget of historical and current land use change, timber harvest, and deforestation in the tropics and the Northern Hemisphere.**

Manipulative Experiments

Manipulative experiments play a unique role in global change research. They allow direct study of many key ecosystem processes that have strong control over the carbon cycle. These experiments can contribute to carbon cycle research in at least three ways. First, global changes in the coming decades will create a range of novel conditions, some of which will very likely be far enough outside the envelope of current and past conditions that observational data alone cannot provide a sufficient basis for credible modeling. Experiments will be especially important in assessing responses to multiple, interacting changes, and in helping to assess slowly developing responses, such as changes in biodiversity. Second, model development and testing solely against observations of current patterns cannot provide the rigor and level of credibility that comes from validation against carefully designed experiments. And third, explaining and illustrating the future trajectory of the carbon cycle can be substantially enhanced through experimental manipulations. Even if the scientific community believes the models, the illustrative value of a solid experiment to the broader public is invaluable.

For manipulative experiments to yield large payoffs, they will need to be tightly integrated with observations and models. Targeted work must address key uncertainties. Interpreting results from manipulative experiments has presented major challenges in the past, especially those relating to the experiments' small spatial scale, short temporal scale, and incomplete coverage of relevant ecosystem processes. Interpretations will certainly continue to be difficult, but these difficulties can be managed through careful selection of study systems, precise definition of key questions, and strong emphasis on integrating the experiments with one another and with other components of carbon cycle research.

Experiments can play an essential role in reducing uncertainties about the location of and the mechanisms underlying current terrestrial and oceanic sinks. Critical targets for experimental work include evaluating the

consequences of the CO_2 increase from preindustrial levels to the present;the relative contributions of forest regrowth,nitrogen deposition,and elevated CO_2 to the current carbon sink; and the interactions between ecological changes and altered climate and atmosphere. To understand the likely future trajectory of the terrestrial sink, manipulative experiments should be used to examine ecosystem responses to simultaneous variation in multiple environmental factors, and to integrate biogeochemical responses with species changes,including alterations in biodiversity. Prototype ocean manipulation experiments showed the importance of iron as a control on carbon uptake by ocean biota in the "high-nutrient,low-chlorophyll" (HNLC) environments of the Equatorial Pacific (Coale et al. 1996). A similar experiment was recently conducted in the Southern Ocean. Such prototype experiments show the potential for using ocean manipulation experiments to understand complex nutrient and ecosystem interactions related to the role of ocean biota in the carbon cycle. Future research should also include manipulation experiments to elucidate the role of iron in biological nitrogen fixation (Falkowski et al. 1998, Karl et al. 1997). Manipulative experiments should not be considered full simulations of the future. They are almost inevitably imperfect as simulations, even when they provide unique and critical insights into underlying mechanisms.

Model Development: Understanding and Predicting Critical Processes

Quantitative understanding of critical processes, processes that operate on time scales from seasons to decades and longer, is essential to predict future atmospheric concentrations of CO_2. Policy decisions affecting future CO_2 emissions—whether to implement restraints or management,or to abstain from doing so—require the capability to predict terrestrial and oceanic carbon sinks. The models to serve these purposes are also necessary to analyze observations and determine optimal sampling strategies.

Predicting these sinks will require the development of coupled terrestrial biosphere–atmosphere–ocean climate models. Many scientific issues need to be solved to improve current predictive capability. The magnitude of the present oceanic sink is reasonably well known (or constrained),but the spatial distribution and evolution of the oceanic sink over time are poorly known. The ability to predict the future behavior of the ocean sink is complicated by the likelihood of large changes in ocean circulation as predicted by coupled climate models and observed in previous periods of rapid climate change. Particular importance attaches to the Southern Ocean,a vast region for which there is a paucity of data. The possible role of changing species composition of marine biotic communities in modifying the carbon sink has only begun to be explored. ***Another major hypothesis that has guided the preparation of this plan is that the oceanic inventory of anthropogenic CO_2 will continue to increase in response to rising atmospheric CO_2 concentrations, but the rate of increase will be modulated by changes in ocean circulation, biology, and chemistry.***

Better understanding of the terrestrial sink is also needed. Current estimates are derived primarily from the mass balance of CO_2 in the atmosphere combined with information about fossil fuel input and ocean CO_2 fluxes. There is growing consensus that a terrestrial sink exists, but the magnitude and underlying causes are uncertain. Estimates of the magnitude of this sink vary by at least a factor of two. Potential underlying mechanisms include recovery from prior land use, lengthening of the growing season due to warming,CO_2 and nitrogen fertilization, and burial of carbon in sediments and rice paddies. Inventories based on direct estimates of wood volume in U.S. forests suggest a smaller sink than do atmospheric estimates.

Carbon sources and sinks,and especially those susceptible to human perturbation,whether inadvertent or intentional,are highly variable over subcontinental and subbasin scales. Hence, information to evaluate the effects of ongoing land use and possible options for mitigation and/or adaptation will be required to significantly improve models of regional CO_2 exchanges. This endeavor requires much greater understanding of how overall patterns of change (natural or human-induced) in critical terrestrial and marine ecosystems might affect fluxes of carbon to the atmosphere. For example,how might climate-related changes in productivity in coastal ecosystems affect the role of marine ecosystems in the cycling of carbon? What conditions and constraints are most important in influencing a region's role as a source or sink for CO_2, and how might these conditions change in the future? What is the long-term photosynthetic and species distribution response of terrestrial ecosystems to climatic anomalies and long-term trends,and how does this determine the carbon uptake? In this context,a focused carbon and climate research program should be viewed as an important component of a broader scientific effort to understand large-scale ecosystem dynamics and change (such as the effort proposed in the recent NRC "Pathways" report [NRC 1998]).

The development of carbon cycle models must be carried out within a framework of rigorous comparison with observations,as well as inter-model comparisons. It is not enough that models make accurate predictions on the whole;their crucial components must also be tested against the data.

Structure of the Plan

Achieving the important goals of a good carbon cycle science program will require a new level of scientific and programmatic integration. Scientifically, it is necessary to have a more complete picture of the ocean-land-atmosphere interactions of the carbon and climate system. Also needed is more thorough understanding of the physical and biogeochemical processes that characterize and control this system. This knowledge must encompass relatively long-term processes that are difficult to study, such as natural and human-mediated disturbance, land use and their impacts on ecological processes such as succession. Programmatically, it is necessary to implement a program that effectively integrates sustained monitoring activities, field and laboratory research, modeling and analytical studies, and targeted assessment activities designed to meet the information needs of society. These goals are attainable. And their attainment has an urgency increasingly recognized in the policy arena.

This plan provides a blueprint for a carbon cycle science program that focuses this renewed commitment. The plan is organized into the following chapters:

Chapter 2 describes the past and present carbon cycle, addressing the question: What has happened to the CO_2 that has already been emitted through human activities (anthropogenic carbon dioxide)?

Chapter 3 explores the critical scientific issues for predicting the future carbon cycle, addressing the question: What will be the future atmospheric carbon dioxide concentrations resulting from both past and future emissions?

Chapter 4 describes the proposed Carbon Cycle Science Program.

Chapter 5 estimates the resource requirements to implement the proposed program.

Chapter 6 discusses the program implementation principles and critical partnerships required for a successful program (including issues related to multidisciplinary research, interagency coordination, laboratory–university–private sector collaborations, international programs, and facilities and infrastructure).