# CHAPTER 9

# CARBON CYCLE

*from the*

## Strategic Plan
## for the
## Climate Change Science Program

By the agencies and staff of the
US Climate Change Science Program

**Review draft dated 11 November 2002**

**Contents**




US Climate Change Science Program
1717 Pennsylvania Ave., NW
Suite 250
Washington, DC 20006
Tel: +1 202 223 6262
Fax: +1 202 223 3065

11 November 2002

Dear Colleague,

The Climate Change Science Program will hold the U.S. Climate Change Science Program Planning Workshop for Scientists and Stakeholders at the Marriott Wardman Park Hotel in Washington, D.C., from 3-5 December 2002. The purpose of the Workshop is to provide a comprehensive review of the discussion draft of the Strategic Plan for U.S. climate change and global change research. This Workshop will offer extensive opportunities for the scientific and stakeholder communities to provide comment and input to the Climate Change Science Program Strategic Plan. When finalized by April 2003, the Strategic Plan will provide the principal guidance for U.S. climate change and global change research during the next several years, subject to revisions as appropriate to respond to newly developed information and decision support tools.

We are writing to request your comments on the discussion draft of the Climate Change Science Program Strategic Plan. Comments on all elements of the plan from all communities are essential in order to improve the plan and identify gaps. In your review, we ask you to provide a perspective on the content, implications, and challenges outlined in the plan as well as suggestions for any alternate approaches you wish to have considered, and the types of climate and global change information required by policy makers and resource managers. We also ask that you comment on any inconsistencies within or across chapters, and omissions of important topics. For any shortcomings that you note in the draft, please propose specific remedies. To participate in the review it is not necessary that you review the entire plan.

We ask that comments be submitted by E-mail to <comments@climatescience.gov>. All comments submitted by 13 January 2003 will be posted on the <http://www.climatescience.gov> website for public review. While we are unable to promised detailed responses to individual comments, we confirm that all submitted comments will be given consideration during the development of the final version of the Strategic Plan.

Attached to this letter are instructions and format guidelines for submitting review comments. Following the instructions will ensure that your comments are properly processed and given appropriate consideration. If you wish to distribute copies of the plan to colleagues to participate in the review, please provide them with a copy of this letter as well as the attached instructions and format guidelines. We have posted the plan on the workshop website at <http://www.climatescience.gov>. PDF files for individual chapters of the plan can be downloaded from this site. If you have any questions, please contact: Sandy MacCracken at 1-202-419-3483 (voice), 1-202-223-3065 (fax), or via the address in the footer below.

We appreciate your contribution of time and expertise to this review, and look forward to your response.

Sincerely,

James R. Mahoney, Ph.D.
Assistant Secretary of Commerce for Oceans and Atmosphere, and
Director, U.S. Climate Change Science Program

## Instructions For Submission of Strategic Plan Review Comments

Thank you for participating in the review process. Please follow the instructions for preparing and submitting your review. Using the format guidance described below will facilitate our processing of reviewer comments and assure that your comments are given appropriate consideration. An example of the format is also provided. Comments are due by **13 January, 2003**.

- Select the chapter(s) or sections of chapters which you wish to review. It is not necessary that you review the entire plan. In your comments, please consider the following issues:
  - **Overview**: overview on the content, implications, and challenges outlined in the plan;
  - **Agreement/Disagreement**: areas of agreement and disagreement, as appropriate;
  - **Suggestions**: suggestions for alternative approaches, if appropriate;
  - **Inconsistencies**: inconsistencies within or across chapters;
  - **Omissions**: omissions of important topics;
  - **Remedies**: specific remedies for identified shortcomings of the draft plan;
  - **Stakeholder climate information**: type of climate and global change information required by representative groups;
  - **Other:** other comments not covered above.
- Please do not comment on grammar, spelling, or punctuation. Professional copy editing will correct deficiencies in these areas for the final draft.
- Use the format guidance that follows for organizing your comments.
- Submit your comments by email to <comments@climatescience.gov> by 13 January, 2003.

## Format Guidance for Comments

Please provide background information about yourself on the first page of your comments: your name(s), organization(s), area of expertise(s), mailing address(es), telephone and fax numbers, and email address(es).

- Overview comments on the chapter should follow your background information and should be numbered.
- Comments that are specific to particular pages, paragraphs or lines of the chapter should follow your overview comments and should identify the page and line numbers to which they apply.
- Comments that refer to a table or figure should identify the table or figure number. In the case of tables, please also identify the row and column to which the comment refers.
- Order your comments sequentially by page and line number.
- At the end of each comment, please insert your name and affiliation.

## Format Example for Comments

### I. Background Information

**Name(s):** John Doe
**Organization(s):** University College
**Mailing Address(es):** 101 1st Street, New York, New York, 10001
**Phone (s)**: 800-555-5555
**Fax(es):** 800-555-6666
**E-mail(s):** John.Doe@univ.edu
**Area of Expertise:** Atmospheric Composition

### II. Overview Comments on Chapter 5: Atmospheric Composition

**First Overview Comment:** (Comment)
**Reviewer's name, affiliation:** John Doe, University College

**Second Overview Comment:** (Comment)
**Reviewer's name, affiliation:** John Doe, University College

### III. Specific Comments on Chapter 5: Atmospheric Composition

Page 57, Line 5: (Comment)
John Doe, University College

Page 58, Line 32 - Page 59, Line 5: (Comment)
John Doe, University College

Table 1-4, Row 3, Column 6: (Comment)
John Doe, University College

Please send comments by email to <comments@climatescience.gov>

# Foreword

In February 2002 President George W. Bush announced the formation of a new management structure, the Climate Change Science Program (CCSP), to coordinate and direct the US research efforts in the areas of climate and global change. These research efforts include the US Global Change Research Program (USGCRP) authorized by the Global Change Research Act of 1990, and the Climate Change Research Initiative (CCRI) launched by the President in June 2001 to reduce significant uncertainties in climate science, improve global climate observing systems, and develop resources to support policymaking and resource management.

The President's Climate Change Research Initiative was launched to provide a distinct focus to the 13-year old Global Change Research Program. The CCRI focus is defined by a group of uncertainties about the global climate system that have been identified by policymakers and analyzed by the National Research Council in a 2001 report requested by the Administration.

The Climate Change Science Program aims to balance the near-term (2- to 4-year) focus of the CCRI with the breadth of the USGCRP, pursuing accelerated development of answers to the scientific aspects of key climate policy issues while continuing to seek advances in the knowledge of the physical, biological and chemical processes that influence the Earth system.

This *discussion draft* strategic plan has been prepared by the thirteen federal agencies participating in the CCSP, with input from a large number of scientific steering groups and coordination by the CCSP staff under the leadership of Dr. Richard H. Moss, to provide a vehicle to facilitate comments and suggestions by the scientific and stakeholder communities interested in climate and global change issues.

We welcome comments on this draft plan by all interested persons. Comments may be provided during the US Climate Change Science Program Planning Workshop for Scientists and Stakeholders being held in Washington, DC on December 3 – 5, 2002, and during a subsequent public comment period extending to January 13, 2003. Information about the Workshop and the written comment opportunities is available on the web site www.climatescience.gov. A specially formed committee of the National Research Council is also reviewing this draft plan, and will provide its analysis of the plan, the workshop and the written comments received after the workshop. A final version of the strategic plan, setting a path for the next few years of research under the CCSP, will be published by April 2003. We appreciate your assistance with this important process.

James R. Mahoney, Ph.D.
Assistant Secretary of Commerce for Oceans and Atmosphere, and
Director, Climate Change Science Program

# Table of Contents
# of the
# Strategic Plan for the Climate Change Science Program

# CHAPTER 9

# CARBON CYCLE

**This chapter's contents…**

Question 1: What are the magnitudes and distributions of North American carbon sources and sinks and what are the processes controlling their dynamics?

Question 2: What are the magnitudes and distributions of ocean carbon sources and sinks on seasonal to centennial time scales, and which processes control their dynamics?

Question 3: What are the magnitudes and distributions of global terrestrial, oceanic, and atmospheric carbon sources and sinks and how are they changing over time?

Question 4: What are the effects of past, present, and future land use change and resource management practices on carbon sources and sinks?

Question 5: What will be the future atmospheric carbon dioxide and methane concentrations, and how will terrestrial and marine carbon sources and sinks change in the future?

Question 6: How will the Earth system, and its different components, respond to various options being considered by society for managing carbon in the environment, and what scientific information is needed for evaluating these options?

Key Linkages

Carbon is important as the basis for the food and fiber that sustain and shelter human populations, as the primary energy source that fuels economies, and as a major contributor to the planetary greenhouse effect and potential climate change. Atmospheric concentrations of carbon dioxide ($CO_2$) and methane ($CH_4$) have been increasing for about two centuries as a result of human activities. Future atmospheric concentrations of these greenhouse gases will depend on trends and variability in natural and human-caused emissions, and the capacity of terrestrial and marine sinks to absorb and retain carbon.

Elevated atmospheric $CO_2$ concentrations, additions of nutrients, and changes in land management practices can significantly enhance (and sometimes reduce) ecological carbon sinks. Engineering approaches for carbon sequestration provide additional options to reduce atmospheric greenhouse gas concentrations or reduce their rate of increase. However, uncertainties remain about how much additional carbon storage could be achieved, the efficacy and longevity of carbon sequestration approaches, whether they will lead to unintended environmental consequences, and just how vulnerable or resilient the global carbon cycle is to such manipulations. Successful carbon management strategies will require solid scientific information about the basic processes of the carbon cycle and an understanding of its long-term interactions with other components of the Earth system such as climate and the water and nitrogen cycles. Breakthrough advances in techniques to observe and model the atmospheric, terrestrial, and oceanic components of the carbon cycle have readied the scientific community for a concerted research effort to identify, characterize, quantify, and predict the major regional carbon sources and sinks—with North America as a near-term priority.

The overall goal for the US Carbon Cycle Science Program research is to provide critical scientific information on the fate of carbon in the environment and how cycling of carbon might change in the future, including the role of and implications for societal actions. In this decade, research on the carbon cycle will focus on two overarching questions:

- **How large and variable are the dynamic reservoirs and fluxes of carbon within the Earth system, and how might carbon cycling change and 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?**

National and international decisionmakers have called for better information on the global carbon cycle in order to reduce uncertainties concerning the potential for climate change and to evaluate carbon sequestration options for climate change mitigation. A well-coordinated, interagency, and multidisciplinary research strategy, bringing together a broad range of needed infrastructure, resources, and expertise, will be essential in providing this information. Specific research questions that will be addressed in support of the two overarching questions are covered in the following sections.

## Question 1: What are the magnitudes and distributions of North American carbon sources and sinks and what are the processes controlling their dynamics?

### STATE OF KNOWLEDGE

There is growing evidence of a current Northern Hemisphere terrestrial sink averaging 1.8 billion metric tons of carbon per year. Recent work suggests that this sink may be a result of land use change, including recovery of forest cleared for agriculture in the last century, and land management practices, such as fire suppression. Other studies suggest that elevated $CO_2$, nitrogen deposition, and changes in regional rainfall patterns also play a role. Atmospheric studies indicate that the terrestrial sink varies significantly from year to year. Current estimates of regional distributions of carbon sources and sinks derived from atmospheric and oceanic data differ from forest inventory and terrestrial ecosystem model estimates. The Carbon Cycle

Science Program has created a structure for coordinating observational, experimental, analytical, and data management activities needed to address the discrepancies, to reduce the errors, and produce a consistent result for North America in a North American Carbon Program (NACP). Assuming corresponding international research projects in Europe and Asia, this research will contribute to improving estimates of quantities, locations, and uncertainties of the Northern Hemisphere carbon sink.

## ILLUSTRATIVE RESEARCH QUESTIONS

- How large and variable are North American carbon sources and sinks?
- What are the most important mechanisms, both natural and human caused, that control North American carbon sources and sinks, and how will they change in the future?
- How much do North America and adjacent ocean basins contribute to the Northern Hemisphere carbon sink?

## RESEARCH NEEDS

Continued and enhanced NACP research will require multidisciplinary investigation of atmospheric concentrations, vertical profiles, and transport of $CO_2$ and $CH_4$; micrometeorological estimates of net $CO_2$ and $CH_4$ fluxes with accompanying biometric measurements at ecosystem and landscape scales; biomass and soil inventories of carbon in forests, crop and range lands, and unmanaged ecosystems; coastal zone carbon processes; and carbon modeling to integrate and assimilate diverse sources of data. A field program, with intensive campaigns and remote sensing of productivity and land cover, will be conducted initially at a central location in the United States, and subsequently expanded to include the entire continent. Research on ecosystem and ocean margin processes that control carbon exchange, including experimental work, will be needed to explain changes in sources and sinks and to parameterize models. Improved ecosystem, inverse, and data assimilation modeling approaches will be needed to analyze carbon source and sink dynamics.

## PRODUCTS AND PAYOFFS

- Prototype *State of North American Carbon Report* (2 years).
- Quantitative measures of atmospheric $CO_2$ and $CH_4$ concentrations in undersampled locations (2-4 years).
- Carbon cycle models: customized for North America (2-4 years); with improved physical controls and characterization of respiration (2 years); and the first carbon data assimilation models (2-4 years).
- Quantitative estimates of carbon fluxes from managed and unmanaged ecosystems in North America, with regional specificity and uncertainties quantified (> 4 years).
- Landscape-scale estimates of carbon stocks in agricultural, forest and range systems and unmanaged ecosystems from spatially resolved carbon inventory and remote sensing data (> 4 years).
- Identification of the processes controlling carbon sources and sinks through manipulative experiments, studies of disturbance, and integration of decision sciences and risk management studies (> 4 years).

- Comprehensive *State of North American Carbon Report* (> 4 years).

New data and models will provide enhanced capability for estimating the future capacity of carbon sinks, which will guide full carbon accounting on regional and continental scales. These results are a prerequisite for planning, implementing, and monitoring carbon sequestration practices in North America. Decisionmakers will receive a series of increasingly comprehensive and accurate reports about the status and trends of carbon emissions and sequestration in North America for use in policy formulation and resource management.

## Question 2: What are the magnitudes and distributions of ocean carbon sources and sinks on seasonal to centennial time scales, and which processes control their dynamics?

### STATE OF KNOWLEDGE

The ocean plays a significant role in the global carbon cycle. Globally, the ocean's net uptake of carbon is estimated to be approximately 2 billion metric tons of carbon per year. However, uncertainties remain in this estimate due to regional variations in ocean uptake, seasonal to interannual variation in nutrient supply, and inadequate representation of coastal margins in models. The discovery that iron is a limiting nutrient for major regions of the world's ocean has profound implications for understanding controls on ocean carbon uptake, as well as for evaluating carbon management options. Estimates of regional ocean sinks can now be used in combination with atmospheric data to constrain estimates of terrestrial carbon sinks. Near-term focus will be on the North Atlantic, North Pacific, and Southern Oceans to provide independent constraints on estimates of the Northern Hemisphere carbon sink.

### ILLUSTRATIVE RESEARCH QUESTIONS

- What are the locations and magnitudes of global ocean carbon sources and sinks?
- What biogeochemical, ecological, and physical processes control the uptake and release of carbon in the ocean, and how may these processes change in the future due to elevated atmospheric $CO_2$ and climate change?

### RESEARCH NEEDS

The Carbon Cycle Science Program will need to continue and enhance ocean observations (*in situ* and remotely-sensed) to track the fate of carbon in the ocean, characterize fluxes of $CO_2$ from the land and atmosphere to the ocean over large space and time scales, and to achieve process-level understanding of the physical and biological controls on those fluxes now and in the future. The program will generate data required to support the development and implementation of models linking climate, ocean circulation, and ocean carbon biogeochemistry to assess more accurately the relationship of carbon sources and sinks to global and climatic change. Focused process studies in the North Atlantic, North Pacific, and along the margins of those basins, including inputs from rivers, are needed in the next several years to permit quantification of the Northern Hemisphere carbon sink and to develop needed understanding of the mechanisms and magnitudes of carbon exchange between land, sea, and air. In 5-10 years, an intensive Southern Ocean carbon program will be needed to resolve uncertainties in the size, dynamics, and global significance of the Southern Ocean as a carbon sink as well as the processes controlling this sink.

**PRODUCTS AND PAYOFFS**

- Greater understanding of the role of nutrients (including iron inputs), phytoplankton functional groups, and primary productivity on deep-sea carbon storage (2-4 years).
- Models of ocean carbon cycling based on linkages between carbon and nitrogen in coastal environments (2-4 years).
- Quantification of global air-sea fluxes of $CO_2$, delivery of carbon from the land to the ocean, and the spatial distribution of carbon in the ocean on seasonal to interannual time scales using remote measurements and *in situ* measurements from newly-developed autonomous $CO_2$ sensors (> 4 years).
- Models of ocean carbon sequestration that incorporate biogeochemistry, ocean circulation, and the potential impact on ecosystems (> 4 years).

This research will quantify the capacity of the oceans to absorb fossil fuel $CO_2$ and remove carbon from the Earth's dynamic reservoirs through export to the deep sea. Uncertainties in the size of the global oceanic carbon sink will be reduced. Information will be provided on the effects of deliberate carbon management approaches for the ocean.

## Question 3: What are the magnitudes and distributions of global terrestrial, oceanic, and atmospheric carbon sources and sinks and how are they changing over time?

**STATE OF KNOWLEDGE**

A major advance in the past decade has been the ability, enabled by new techniques for atmospheric measurement, to distinguish the roles of the ocean and land in the uptake and storage of atmospheric carbon. Inverse modeling approaches are beginning to allow continental-scale resolution of sources and sinks, but with significant uncertainties. Key processes dominating uptake and release of carbon can vary in different regions of the world, and can change in response to changes in natural and human forcings. New remote sensing observations have engendered a new appreciation for the significant spatial and temporal variability of primary productivity in Earth's ecosystems. There is a growing realization that the carbon cycle must be studied as an integrated Earth system carbon cycle.

**ILLUSTRATIVE RESEARCH QUESTIONS**

- What is the current state of the global carbon cycle?
- What natural processes and human activities control carbon emissions and uptake around the world?

- How will changes in climate, atmospheric $CO_2$ concentration, and human activity influence carbon sources and sinks both regionally and globally?

**RESEARCH NEEDS**

Sustained investments will be needed in the collection, reporting, analysis, and integration of relevant global carbon monitoring and inventory data; in our understanding of carbon cycling processes; and in the development of coupled, interactive carbon-climate and, ultimately, Earth system models. New *in situ* and space-based observational capabilities will be needed. Process studies must focus on characterizing key controls as they vary around the world and on explaining changes in the growth rates of atmospheric $CO_2$ and $CH_4$. Improving models will require development of innovative new assimilation and modeling techniques and rigorous testing, evaluation, and periodic intercomparison. The carbon cycle science program will collaborate with all CCSP research elements to assemble, merge, and analyze carbon, biogeochemical, physical, and socioeconomic information for comprehensive reporting on the state of the global carbon cycle. An ongoing dialogue with stakeholders will be essential to ensure that the carbon cycle information provided will be useful. Continued international cooperation will be necessary to achieve results and ensure widespread utility.

**PRODUCTS AND PAYOFFS**

- US component of international carbon observing system, including carbon storage, fluxes, and complementary environmental data (ongoing; enhancements within 2 years).
- Identification and quantification of the processes controlling soil carbon storage and global $CO_2$ exchange among the land, ocean, and atmosphere (2-4 years).
- First prototype *State of the Global Carbon Cycle Report* (4 years).
- Global maps of carbon storage derived from model-based analysis of actual land cover (1 kilometer resolution: 2 years; 30 meter resolution: > 4 years).
- Estimates of carbon flux strength in remaining regions of the world with significant uncertainties (i.e., regions not addressed in questions 1 and 2 above) (Amazon forest: 2-4 years; Northern Eurasia: 4 years; Pan-tropics: > 4 years; balanced global carbon budget: > 4 years).
- Global, synoptic data products from satellite remote sensing documenting changes in primary productivity, biomass, vegetation structure, land cover, and atmospheric column $CO_2$ (all but $CO_2$ ongoing; $CO_2$ > 4 years).
- Evaluation of the potential for dramatic changes in carbon storage and fluxes due to changes in climate, atmospheric composition, and ecosystem disturbance, and characterization of potential feedbacks to the climate system (> 4 years).
- Full *State of the Global Carbon Cycle Report* (> 4 years).

Policymakers and resource managers will be provided with consistent, integrated, and quantitative information on global carbon sources and sinks that can be used in national and worldwide carbon accounting and for evaluating carbon management activities. Improved global carbon models and understanding of key process controls on carbon uptake and emissions, including regional variations, will be made available to improve applied climate models and inform scenario development for decision support.

## Question 4: What are the effects of past, present, and future land use change and resource management practices on carbon sources and sinks?

### STATE OF KNOWLEDGE

Historic and current land use changes and resource management practices impact the overall carbon cycle. For example, there has been widespread reforestation since 1900 in the eastern United States following the movement of agricultural production toward the Midwest. Forest growth and conversion of forests to long-lived wood products increase the carbon stored in the forest products pool. Better land management practices (e.g., reduced soil tillage in cropping systems), increased agricultural productivity, and conversion from cropland to grassland can increase carbon storage in soil. However, changes in land use and management, such as clearing forests and grasslands and intensive tillage and harvest practices, release $CO_2$ to the atmosphere. Research in this area will require collaboration with the Land Use and Land Cover Change research element to document global patterns of land use and land cover and to understand changes in them, along with land management practices, as powerful drivers of terrestrial carbon sinks and sources. This information highlights an urgent need for improved understanding of the processes of land use change and the impacts of environmental and resource management decisions.

### ILLUSTRATIVE RESEARCH QUESTIONS

- What are the roles of past and current land use and management in terrestrial carbon sources and sinks at local to continental scales?
- How do resource management practices and likely future changes in management affect carbon that is stored in terrestrial ecosystems and durable products?
- How do social, political, and economic forces influence human decisions regarding land use and resource management, and how might changes in these forces affect the carbon cycle?

### RESEARCH NEEDS

Maintenance and enhancement of the data collection and synthesis capabilities of national networks of long-term experimental sites in forests, rangelands, wetlands, agricultural lands, and other ecosystems is needed to provide an essential foundation of ecosystem monitoring data. US Carbon Cycle research will collaborate closely with operational resource management and inventory programs to ensure the availability of these needed long-term observations of ecological processes, environmental changes and impacts, and treatment effects. Continued monitoring of carbon storage and fluxes (in soil, litter, vegetation, forest products, and woody debris) and their response to various land use changes and resource management practices will be required to accurately quantify the role of land cover and use change in the global carbon cycle. Continued satellite land cover data products and new remote sensing estimates of aboveground biomass are needed. Process studies linked with observations and long-term manipulative experiments will be required to identify cause-and-effect relationships. Models are needed to link ecosystem, management, policy, and socioeconomic factors to better project future changes in both carbon storage and flux and land use and development.

**PRODUCTS AND PAYOFFS**

- Database of agricultural management effects on carbon emissions and sequestration in the United States (2 years).
- Syntheses of effects of land cover and land use change on carbon sources and sinks in Amazonia (2-4 years), Northern Eurasia (4 years), and the Pan-tropics (> 4 years).
- Evaluation of the impacts of disturbance (e.g., fire, logging, and land conversion) on the fate of carbon in selected ecosystems (2 years) and additional major ecosystems (> 4 years).
- Quantification of the effects of different land use changes and management practices on biomass and soil carbon storage and release (> 4 years).
- Analysis of the effects of historical and contemporary land use on carbon storage and release across environmental gradients (> 4 years).
- Linked ecosystem, resource management, and human dimensions models that enable scientific evaluation of a wide range of policy scenarios and assessment of effects on carbon sequestration, market prices, land allocation decisions, and consumer and producer welfare (> 4 years).

Quantifying past and current effects of land use change and resource management on the carbon cycle will enable policymakers and resource managers to predict how current activities will affect the carbon cycle at multiple scales and to develop alternative policies and practices to mitigate the continued buildup of atmospheric carbon (e.g., carbon sequestration through agricultural management practices).

## Question 5: What will be the future atmospheric carbon dioxide and methane concentrations, and how will terrestrial and marine carbon sources and sinks change in the future?

**STATE OF KNOWLEDGE**

Accurate projections of future atmospheric $CO_2$ and $CH_4$ levels are critically needed to calculate radiative forcings in models that project changes in climate and their impact on the sustainability of natural resources and human populations. Changes in the size or intensity of terrestrial and marine carbon sinks directly affect the amount of carbon emissions that remain in the atmosphere, and, thus, must be projected as well. There are several different types of carbon models available, but most lack complete integration of all components, interactive coupling, and/or full validation. While no one of these models is ideal, as a group they are becoming quite useful for exploring global change scenarios and bounding potential future $CO_2$

conditions and responses of ecosystems. Current models are less useful for projecting future $CH_4$ conditions. Modeling of future carbon conditions will require collaboration with the Human Contributions and Responses and Atmospheric Composition (for $CH_4$) research elements and rely on scenarios requested by decisionmakers and provided by the Scenario Development element.

## ILLUSTRATIVE RESEARCH QUESTIONS

- What are important land use-climate-carbon cycle interactions and feedbacks, and which have the potential to lead to anomalous responses?
- How will carbon sinks and sources respond to future increases in $CO_2$, changes in climate, and inherent natural variability?
- How can we best represent carbon cycle processes in models to produce realistic projections of atmospheric concentrations?
- How will the distribution, strength, and dynamics of global carbon sources and sinks change in the in the next few decades and in the next few centuries?

## RESEARCH NEEDS

Research under this topic area will focus on incorporating improved process understanding into carbon cycle models, developing new generations of terrestrial and ocean carbon exchange models, and developing Earth system models with a dynamic coupling between carbon cycle processes and the climate system. In particular, improved models must address managed as well as natural ecosystems and incorporate the effects of multiple, interacting factors and human influences. Advances in the future will be made through a combination of observations, manipulative experiments, and synthesis via models enabled by increases in computational capabilities. Collaboration with the Ecosystems research element will be essential.

## PRODUCTS AND PAYOFFS

- Advanced carbon models that include the long-term effects of actual land use history (2-4 years).
- Advanced carbon models that are able to simulate interannual variability at ecosystem and landscape scales (2-4 years).
- Synthesis of whole ecosystem response to increasing $CO_2$ based on experimental manipulation of $CO_2$ (2-4 years).
- Analysis of global $CH_4$ dynamics, with the potential for reduced uncertainties, based on a new synthesis of observational data and improved modeling (2-4 years).
- Advanced carbon cycle models that incorporate improved parameterizations based on data from manipulative experiments and soil carbon transformation studies (> 4 years).
- Synthesis of whole ecosystem response to combined warming and increasing $CO_2$ (> 4 years).
- Improved projections of climate change forcings and quantification of dynamic feedbacks among the carbon cycle, human actions, and the climate system, with better estimates of uncertainty and errors, from prognostic carbon cycle models (> 4 years).

New understanding of the controls on carbon cycle processes will be provided to improve parameterizations and/or mechanistic portrayals in climate models. Projections of future atmospheric concentrations of $CO_2$ and $CH_4$ will be made available for use in applied climate models. Both will aid in improving model projections of future climate change and its effects on the Earth system.

## Question 6: How will the Earth system, and its different components, respond to various options being considered by society for managing carbon in the environment, and what scientific information is needed for evaluating these options?

### STATE OF KNOWLEDGE

Questions about the effectiveness of carbon sequestration, the longevity of storage, the practicality of reducing emissions, technological options, resultant impacts on natural and human systems, and the overall economic viability of carbon management approaches create an imperative for better scientific information to inform decisionmaking to manage carbon. Presently, there is limited scientific information to support carbon management strategies, and little is known about the long-term efficacy of new management practices for enhancing carbon sequestration or reducing emissions or how they will affect components of the Earth system. This element links to the National Climate Change Technology Initiative (NCCTI), which focuses on engineered technologies, carbon offsets, and economic systems.

### ILLUSTRATIVE RESEARCH QUESTIONS

- What are potential magnitudes, mechanisms, and longevity of carbon sequestration by terrestrial and marine systems?
- How will elevated $CO_2$, climatic variability and change, and other environmental factors and changes (such as air, water, and land pollution; changing landscapes and natural disturbance; and intrinsic human productivity) affect carbon cycle management approaches?
- What scientific and socioeconomic criteria should be used to evaluate the sensitivity of the carbon cycle and the vulnerability and sustainability of carbon management approaches?

### RESEARCH NEEDS

Research to analyze the effects on terrestrial and marine systems and to scientifically assess the short- and long-term efficacy of carbon management practices is needed. Field studies, manipulative experiments, and model investigations will be needed to evaluate the effectiveness of designed management approaches to manipulate carbon in the ocean, land, and atmosphere, and to assess their impacts on natural and human systems. New monitoring techniques and strategies to measure the efficacy of carbon management activities will also be needed. Experiments and process studies will also be needed to evaluate the likelihood of unintended environmental consequences resulting from enhanced carbon sequestration. Research on the scientific underpinning for carbon management draws upon products from carbon cycle research questions 1-5, and will coordinate with the Ecosystems research element and the NCCTI as well as public and private programs responsible for developing and/or implementing carbon management. Two types of models are required: those that incorporate understanding of basic processes into evaluation of natural and enhanced mechanisms of carbon sequestration, and those that assess the economics of carbon management options in the agricultural and forestry sectors. Research is also needed to support assessments of carbon management and sequestration potentials, decisionmaking processes that involve multiple land management scenarios, and the role of sequestration mechanisms for calculating net carbon emissions intensity.

**PRODUCTS AND PAYOFFS**

- Monitoring techniques and strategies to improve quantitative measurement of the efficacy of carbon management activities (2-4 years).
- Evaluation of the biophysical potential of US ecosystems to sequester carbon (selected regions: 2 years; US: 4 years) and assessment of carbon sequestration management practices in crops and grazing systems (warm and cool season grasses: 2 years; irrigated systems and grazing systems and other crops: 4 years).
- Identification of the effects of enhanced nutrient availability on carbon uptake in the ocean and of elevated $CO_2$ on terrestrial plant physiology and carbon allocation (> 4 years).
- Analysis of options for science-based carbon management decisions and deployment by landowners (> 4 years).
- Scientific criteria and model tests of carbon management sustainability that take into account system interactions and feedbacks (> 4 years).

This research will provide the scientific foundation to inform decisions and strategies for managing carbon stocks and enhancing carbon sinks in terrestrial and oceanic systems. Firm quantitative estimates of key carbon cycle properties (e.g., rate, magnitude, and longevity) will provide fundamental information for projecting carbon sequestration capacity, for calculating net emissions, and for full carbon accounting.

## Key Linkages

US carbon cycle science will be conducted in cooperation with all the other Climate Change Research Initiative (CCRI) and US Global Change Research Program (USGCRP) research elements as well as other research, operational, infrastructure, and technology development programs. Cooperation with programs that provide national computational infrastructure and data management systems will be essential. Collaboration with the Land Use/Land Cover Change research element (Chapter 9) for Carbon Cycle question 4 will be especially critical. The enhanced observational networks needed to address Carbon Cycle questions 1-3 will need to be planned in close coordination with the Climate Quality Observations, Monitoring, and

Data Management element (Chapter 3). Addressing Carbon Cycle question 6 will require scientific studies conducted in close cooperation with the NCCTI and public and private projects that develop and implement management approaches to sequester carbon or reduce emissions. Linkages to Ecosystems (Chapter 10), Water Cycle (Chapter 7), Applied Climate Modeling (Chapter 4), Atmospheric Composition (Chapter 5), Human Contributions and Responses (Chapter 11), Climate Variability and Change (Chapter 6), and Scenario Development (Chapter 4) research elements will also be important.

International cooperation will be necessary to coordinate global observational networks, integrate scientific results from around the world, and ensure widespread utility of the *State of the Carbon Cycle Report* and model projections. Partnerships are anticipated with Integrated Global Observing Strategy (IGOS) Partners and the global observing systems. Interactions with and contributions to the Global Carbon Project of the International Geosphere-Biosphere Programme, the International Human Dimensions Programme, and the World Climate Research Programme will be important. US carbon cycle research will contribute to bilateral activities being developed by the administration.

# Authors and Contributors

## PART II. THE U.S. GLOBAL CHANGE RESEARCH PROGRAM (USGCRP)

### Chapter 9. Carbon Cycle

Lead Authors

Diane E. Wickland (Co-Chair), NASA
Roger Dahlman (Co-Chair), DOE
Jessica Orrego, CCSP
Richard A. Birdsey, USDA
Nancy Cavallaro, USDA
Sue Conard, USDA
Rachael Craig, NSF
Michael Jawson, USDA
Anna Palmisano, DOE
Don Rice, NSF
Ed Sheffner, NASA
David Shultz, USGS
Kathy Tedesco, NOAA
Charles Trees, NASA

Contributors

Enriqueta Barrera, NSF
Marilyn Buford, USDA
Cliff Hickman, USDA
Carol Jones, USDA
Steven Shafer, USDA
Bryce Stokes, USDA