CHAPTER 7

Carbon Cycle

CHAPTER CONTENTS

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. Carbon dioxide (CO_2) is the largest single forcing agent of climate change, and methane (CH_4) is also a significant contributor. Atmospheric concentrations of CO_2 and CH_4 have been increasing for about 2 centuries as a result of human activities and are now higher than they have been for over 400,000 years. Since 1750, CO_2 concentrations in the atmosphere have increased by 30% and CH_4 concentrations in the atmosphere have increased by 150%. Approximately three-quarters of present-day anthropogenic CO_2 emissions are due to fossil-fuel combustion (plus a small amount from cement production); land-use change accounts for the rest. The strengths of CH_4 emission sources are uncertain due to the high variability in space and time of biospheric sources (IPCC, 2001a). 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. The global carbon cycle is depicted in Figure 7-1.

Decisionmakers searching for options to stabilize or mitigate concentrations of greenhouse gases in the atmosphere are faced with two broad approaches for controlling atmospheric carbon concentrations: (1) reduction of carbon emissions at their source, such as through reducing fossil fuel use and cement production or changing land use and management (e.g., reducing deforestation); and/or (2) enhanced sequestration of carbon,either through enhancement of biospheric carbon storage or through engineering solutions to capture carbon and store it in repositories such as the

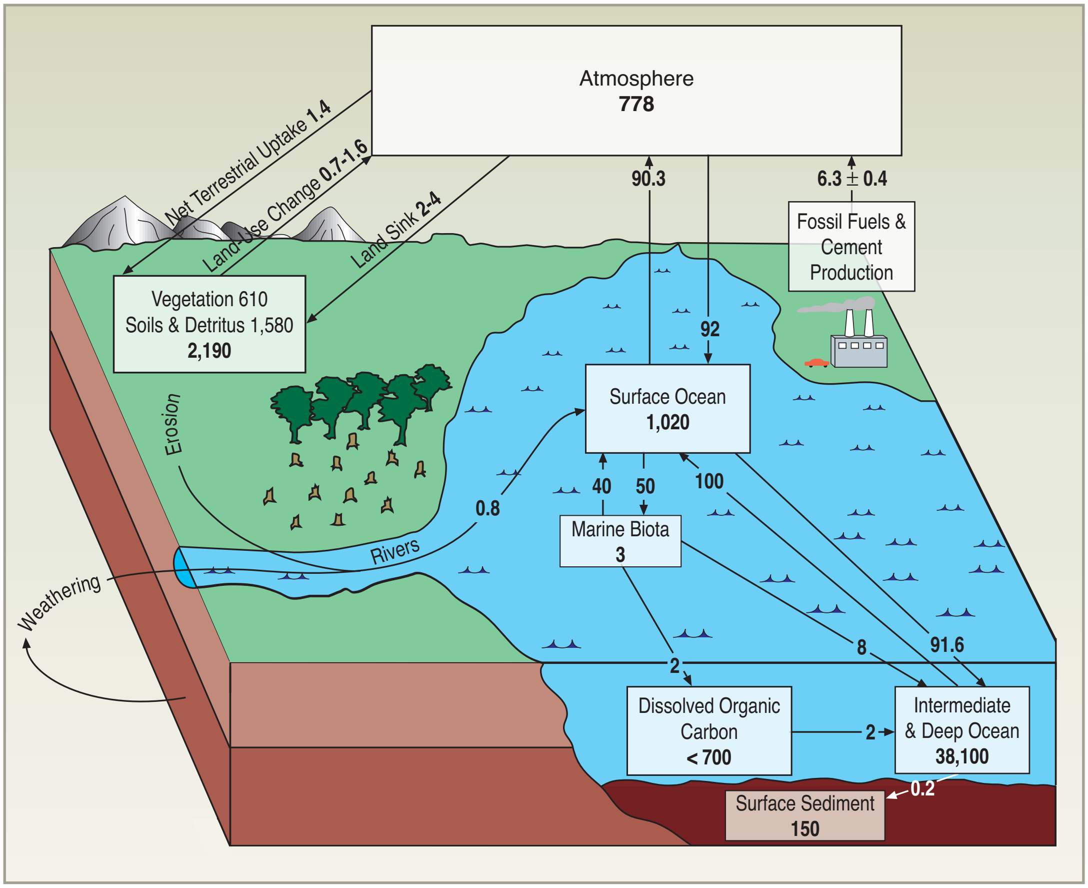

Figure 7-1: The global carbon cycle. Carbon is exchanged among the atmosphere, oceans, and land. This cycling of carbon is fundamental to regulating Earth's climate. In this static figure, the components are simplified and average values are presented. Storages [in petagrams carbon (PgC)] and fluxes (in PgC yr^{-1}) of carbon for the major components of the Earth's carbon cycle are estimated for the 1990s. For more information, see Annex C.

deep ocean or geologic formations. Enhancing carbon sequestration is of current interest as a near-term policy option to slow the rise in atmospheric CO_2 and provide more time to develop a wider range of viable mitigation and adaptation options. However, uncertainties remain about how much additional carbon storage can 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. Such strategies also will require an ability to account for all carbon stocks, fluxes, and changes and to distinguish the effects of human actions from those of natural system variability (see Figure 7-2). Because CO_2 is an essential ingredient for plant growth, it will be essential to address the direct effects of increasing atmospheric concentrations of CO_2 on terrestrial and marine ecosystem productivity. 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 project the major regional carbon sources and sinks—with North America as a near-term priority.

The overall goal for Climate Change Science Program (CCSP) carbon cycle 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 global 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?

A well-coordinated, multidisciplinary research strategy, bringing together a broad range of needed infrastructure, resources, and expertise from the public and private sectors, will be essential to answer these questions. A continuing dialogue with stakeholders, including resource managers, policymakers, and other decisionmakers, must be established and maintained to ensure that desired information is provided in a useful form (NRC, 1999c).

Specific research questions that will be addressed in support of the two overarching questions are covered in the following sections. These six carbon cycle questions focus on research issues of high priority and potential payoff for the next 10 years. They derive from the program goals recommended by the research community in *A U.S. Carbon Cycle Science Plan* (CCWG, 1999). Carbon cycling is an integrated Earth system process and no one of these questions can be addressed in isolation from the others—or without contributions from and interactions with the other research elements of the CCSP, the Climate Change Technology Program (CCTP), and the international scientific community. Many of the research activities, research needs, and milestones, products, and payoffs identified under each question will be relevant to more than one question, indicating a high degree of complementarity across questions.

Question 7.1: What are the magnitudes and distributions of North American carbon sources and sinks on seasonal to centennial time scales, and what are the processes controlling their dynamics?

State of Knowledge

There is compelling evidence of a current Northern Hemisphere extra-tropical terrestrial sink of 0.6-2.3 PgC yr^{-1} (IPCC, 2001a). Recent work suggests that this sink is 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 and reduced tillage of agricultural lands. Other studies suggest that elevated atmospheric CO_2 concentration, nitrogen deposition, changes in growing season duration, and changes in regional rainfall patterns also play a role. Atmospheric studies indicate that the net terrestrial sink varies significantly from year to year (see Figure 7-3).

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, but there is growing confidence that these differences can be reconciled (IPCC, 2000a, 2001a). The Carbon Cycle science program will coordinate the observational, experimental, analytical, and data management activities needed to reconcile the discrepancies, to reduce the uncertainties, and to produce a consistent result for North America through the North American Carbon Program (NACP, 2002). When integrated with results from corresponding international research projects in Europe and Asia (Global Carbon Project, 2003), the results of the NACP will contribute to locating and accurately quantifying the Northern Hemisphere carbon sink.

Illustrative Research Questions

- What is the carbon balance of North America and adjacent ocean basins, and how is that balance changing over time? How large and variable are the sources and sinks, and what are the geographic patterns of carbon fluxes?
- What are the most important mechanisms, both natural and human-induced, 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?

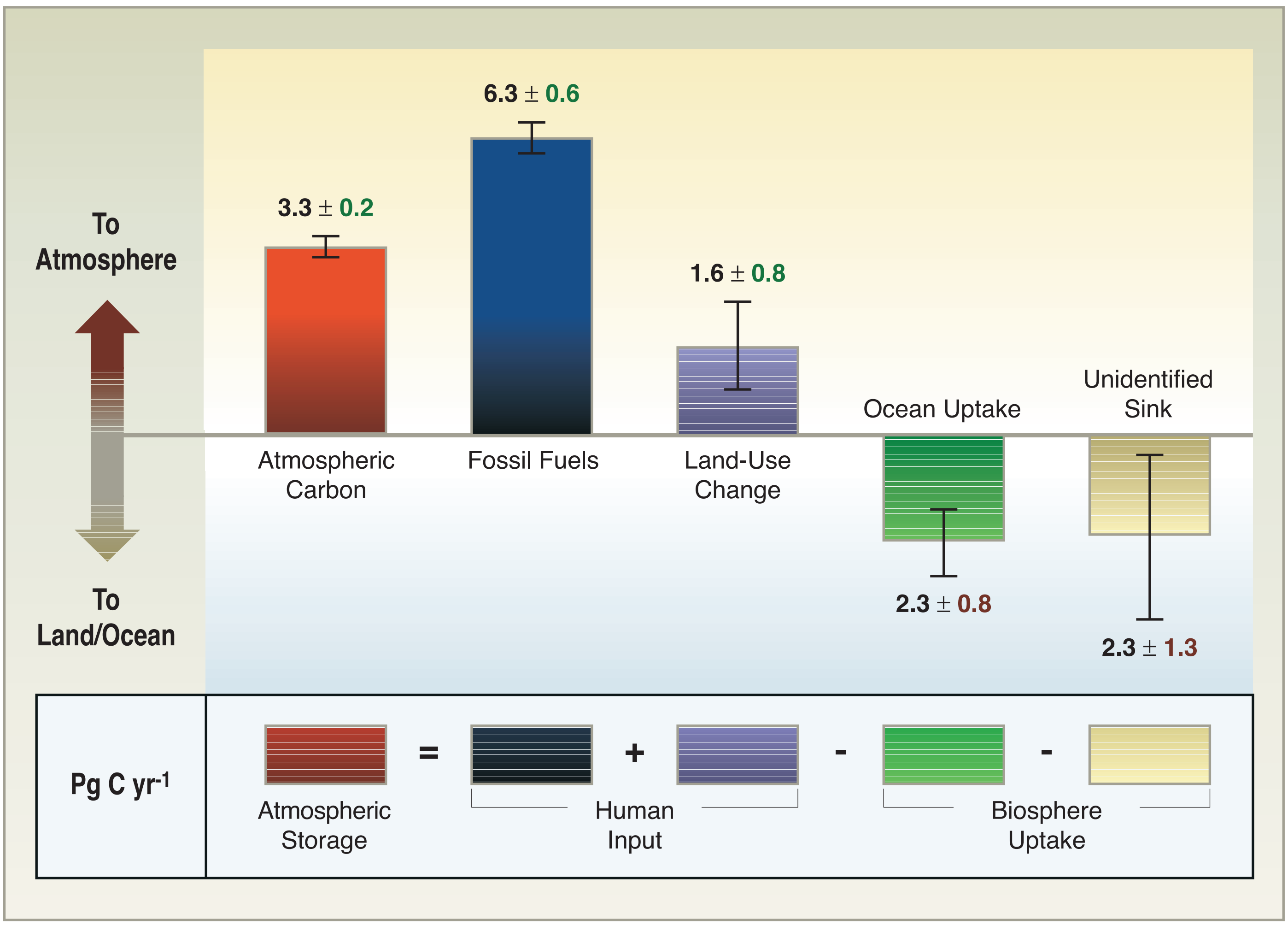

Figure 7-2: Average annual global budget of CO_2 and uncertainties for 1989 to 1998 expressed in PgC yr^{-1}. Error bounds correspond to a 90% confidence interval. The numbers reported here are from *Land Use, Land-Use Change, and Forestry*, a special report of the Intergovernmental Panel on Climate Change (IPCC, 2000a). There is compelling evidence that a large fraction of the "unidentified sink" may be accounted for by uptake in the temperate and/or boreal zones of the terrestrial Northern Hemisphere. Source: F. Hall, Office of Global Carbon Studies, NASA Goddard Space Flight Center.

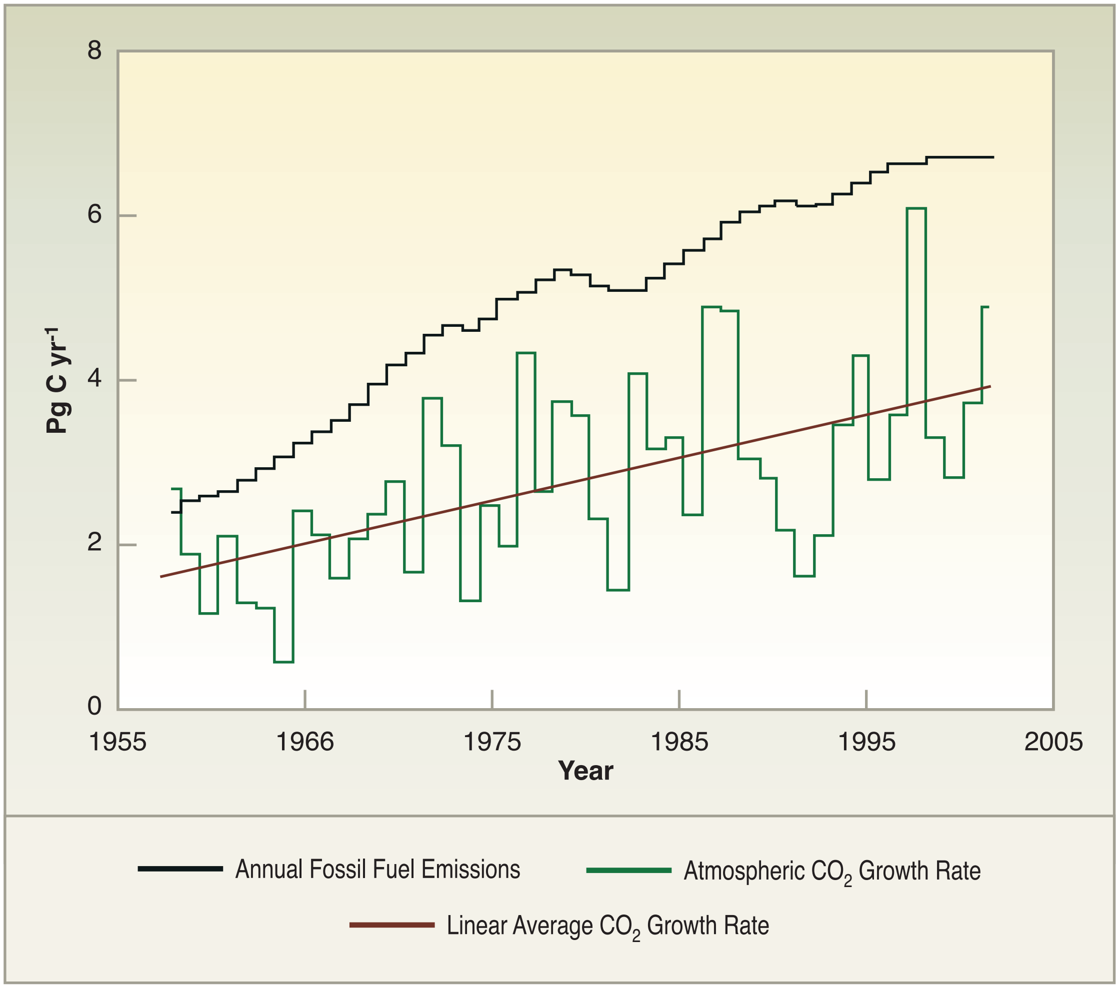

Figure 7-3: Rate of increase of atmospheric CO_2 and fossil-fuel emissions. The upper curve shows the annual global amount of carbon added to the atmosphere (in PgC yr^{-1}) in the form of CO_2 by burning coal, oil, and natural gas. The strongly varying curve shows the annual rate of increase of carbon in the atmosphere. The difference between the two curves represents the total net amount of CO_2 absorbed each year by the oceans and terrestrial ecosystems. For more information, see Annex C.

- Are there potential "surprises," where sources could increase or sinks disappear?

Research Needs

Continued and enhanced NACP research will require multidisciplinary investigations that merge observational, experimental, and modeling approaches at various scales to produce a consistent North American carbon balance (NACP, 2002). Observational needs include reliable measurements of atmospheric concentrations, vertical profiles, and transport of CO_2, CH_4, and related tracers (e.g., the ratio of oxygen to nitrogen (O_2/N_2), CO_2 isotopes); 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 grazing lands, wetlands, and unmanaged ecosystems; monitoring of carbon transport by erosion and rivers; and measurements of coastal ocean carbon constituents, processes, and air-sea and land-ocean fluxes. There is a need for improved measurement technologies and standardization of analytical methods and reference materials. The work to secure the required observational networks and enhancements will need to be closely coordinated with the Climate Change Research Initiative (CCRI) plan for climate-quality observations.

A field program, with intensive campaigns, process studies, and remote sensing of productivity and land cover, will be conducted initially within selected regions of the United States, and subsequently expanded to include the entire continent. Innovative ecosystem, inverse, and data assimilation modeling approaches will be needed to enable comprehensive carbon accounting and improve understanding of North American carbon stocks and flows.

Joint activities with the Water Cycle research element to measure CO_2 and water vapor fluxes and the transport of carbon and nutrients through surface waters and wetlands will be needed to economize on costly field measurements and share expertise. Collaboration with the Ecosystems research element will be needed to characterize process controls on carbon flow through plants, soils, and aquatic systems and to conduct multi-factor manipulative experiments (i.e., experiments in which key environmental factors are varied under controlled conditions) in terrestrial and marine ecosystems. Research on human system influences, requiring inputs from the Human Contributions and Responses research element, will be equally important, especially in studies of emissions from fossil-fuel use; land, animal, and waste management practices; and the effects of adaptation actions implemented at local, state, regional, or national levels.

Milestones, Products, and Payoffs

- Improved methodologies for carbon source and sink accounting in agriculture and forestry [2 years]. This will be an important input for the Decision Support element.
- Quantitative measures of atmospheric CO_2 and CH_4 concentrations and related tracers in under-sampled locations [2-4 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 [beyond 4 years]. This will be an important input for the Ecosystems research element.
- Quantitative estimates of carbon fluxes from managed and unmanaged ecosystems in North America and surrounding oceans, with regional specificity [beyond 4 years]. Measurement sites will be coordinated with the Water Cycle, Ecosystems, and Land-Use/Land-Cover Change research elements.
- Carbon cycle models customized for North America [2-4 years], with improved physical controls and characterization of respiration [2 years] and employing the first carbon data assimilation approaches [2-4 years].
- Prototype *State of the Carbon Cycle* report focused on North America [2 years], followed by a more comprehensive report [beyond 4 years]. This will be a valuable input for the Decision Support element.

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

BOX 7-1

GLOBAL CARBON CYCLE

FY04 CCRI Priority—North America's Carbon Balance
Climate Change Research Initiative research on the carbon cycle will focus on North America's carbon balance. This research will reduce uncertainties related to the buildup of CO_2 and CH_4 in the atmosphere and the fraction of fossil-fuel carbon being taken up by North America's ecosystems and adjacent oceans (NRC, 2001a). This work will be undertaken in the context of the U.S. Global Change Research Program's ongoing North American Carbon Program to quantify the magnitudes and distributions of terrestrial, oceanic, and atmospheric carbon sources and sinks, to understand the processes controlling their dynamics, and to produce a consistent analysis of North America's carbon budget that explains regional and sectoral contributions and year-to-year variations.

The CCRI will augment monitoring capabilities for atmospheric concentrations of CO_2, CH_4, and related tracers. The CCRI will invest in expanding and enhancing the AmeriFlux network, which measures net CO_2 exchange between terrestrial ecosystems and the atmosphere, documenting how much carbon is gained or lost on an annual basis. New experimental studies of carbon cycling processes in forests and soils and new ocean carbon surveys along the continental margins of North America will be conducted. Development of new *in situ* and remote-sensing technologies for measuring atmospheric CO_2 and CH_4 and carbon in plants, soils, and the ocean is being accelerated. New investments in diagnostic analyses and modeling will focus on developing innovative modeling frameworks and model-data fusion approaches that will bring together and ensure synergistic uses of diverse carbon data sets.

These CCRI investments will yield near-term information to be summarized in a first *State of the Carbon Cycle* report focused on North America that will provide: (1) an evaluation of our knowledge of carbon cycle dynamics relevant to the contributions of and impacts on the United States, and (2) scientific information for U.S. decision support focused on key issues for carbon management and policy.

Question 7.2: What are the magnitudes and distributions of ocean carbon sources and sinks on seasonal to centennial time scales, and what are the processes controlling their dynamics?

State of Knowledge

The ocean is the largest of the dynamic carbon reservoirs on decadal to millennial time scales, and ocean processes have regulated the uptake, storage, and release of CO_2 to the atmosphere over past glacial-interglacial cycles. Globally, the ocean's present-day net uptake of carbon is approximately 2 $PgC\ yr^{-1}$ (see Figure 7-4), accounting for the removal from the atmosphere of about 30% of fossil-fuel emissions (IPCC, 2001a). Marine carbon storage is jointly modulated by ocean circulation and biogeochemistry. Physical processes, primarily the ventilation of surface waters and mixing with intermediate and deep waters, have been largely responsible for regulating the historical uptake and storage of this anthropogenic carbon. However, knowledge is not yet sufficient to account for regional, seasonal, or interannual variations in ocean carbon uptake.

There is growing appreciation of the importance and complexity of factors governing the biological uptake of CO_2 and subsequent export of organic carbon to the deep sea (e.g., iron limitation, nitrogen fixation, calcification, aquatic community structure, subsurface re-mineralization). The discovery that iron is a limiting nutrient for major regions of the world's oceans has profound implications for understanding controls on ocean carbon uptake, as well as for evaluating carbon management options. The responses of air-sea CO_2 fluxes and marine ecosystems to daily, seasonal, and interannual variations in nutrient supply and climate are not well documented outside the equatorial Pacific.

Knowledge is also lacking on the magnitudes, locations, and mechanisms of surface carbon export and subsequent re-mineralization in the mesopelagic

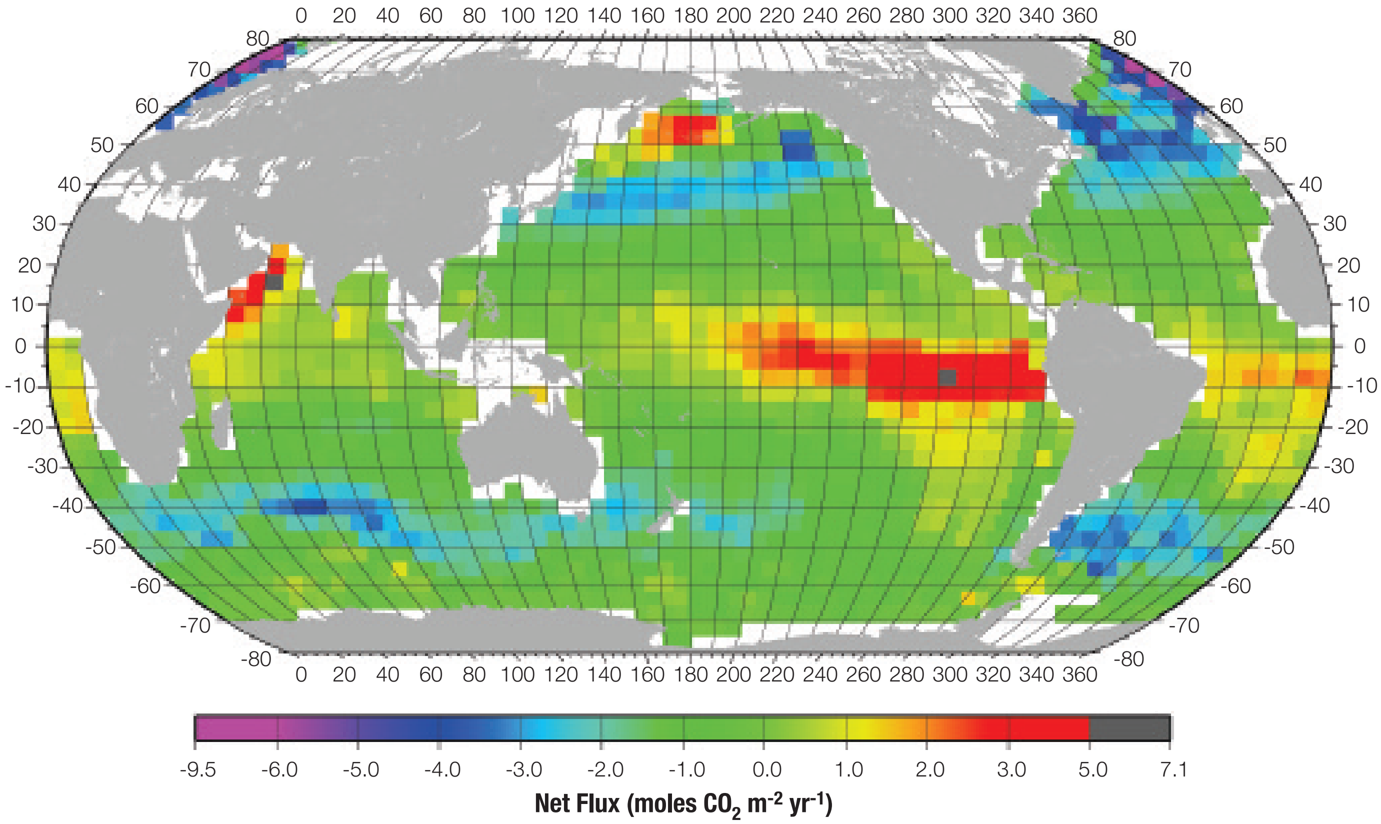

Figure 7-4: Map showing the climatological mean annual distribution of net sea-air CO_2 flux (in moles CO_2 $m^{-2}yr^{-1}$) over the global oceans. The blue-magenta areas indicate that the ocean is a sink for atmospheric CO_2, and the yellow-red areas, a source. The annual CO_2 uptake by the oceans has been estimated to be in the range of 1.5 to 2.1 PgC. Source: T. Takahashi, NOAA Lamont-Doherty Earth Observatory. For more information, see Annex C.

(100-1,000 m) zone, the deep ocean, and sediments. Past analyses have not fully accounted for carbon fluxes and dynamics on continental margins or in the coastal ocean, where sediment-water interactions are significant and terrestrial inputs and human-induced perturbations are large. The future behavior of the ocean carbon sink is most uncertain because of potentially large feedbacks among climate change, ocean circulation, marine ecosystems, and ocean carbon cycle processes (CCOIIG, 2003).

Illustrative Research Questions

- What is the global inventory and geographic distribution of anthropogenic CO_2 in the oceans?
- What is the magnitude, spatial pattern, and variability of air-sea CO_2 fluxes?
- How are the ocean inventories of carbon and related biogeochemical constituents changing over time?
- What biogeochemical, ecological, and physical processes control oceanic uptake and release of carbon, and how may these processes change in the future? What are the major feedback mechanisms and climate sensitivities for ocean carbon storage?
- What quantity of carbon is transported to the oceans from the land and associated freshwater systems, and how much of this carbon contributes to net storage?

Research Needs

CCSP carbon cycle research will need to continue and enhance global ocean observations (*in situ* and remotely sensed) to track the fate of carbon in the oceans, characterize fluxes of carbon and nutrients (e.g., iron, nitrogen, phosphorus), quantify transfers from the land and atmosphere to the ocean over large space and time scales, and understand the physical and biogeochemical processes that control ocean carbon fluxes now and in the future. Global carbon hydrographic surveys, surface water partial pressure of CO_2 (pCO_2) observations, time-series measurements, satellite remote sensing, and a North American coastal observing system are needed to understand the feedback links among the open ocean, ocean margins, the terrestrial environment, and the atmosphere (CCOIIG, 2003; GOOS, 2002; LSCOP, 2002; Ocean Theme Team, 2001).

Enabling activities will be needed in the areas of chemical reference standards, *in situ* sensor and autonomous platform technology development, remote-sensing algorithms and validation, data management and accessibility, and computational capacity for modeling. Research will be required to integrate and reconcile oceanic and atmospheric carbon uptake estimates through enhanced data synthesis and numerical modeling approaches including both forward and inverse models as well as data assimilation. Data from the Climate Variability and Change research element will be needed to support the development and implementation of models linking climate, ocean circulation, ocean carbon biogeochemistry, and marine ecosystem dynamics to assess more accurately the relationship of carbon sources and sinks to global climate change.

Multidisciplinary process studies will be needed to understand the response of ocean ecosystems to interannual climatic variability, biogeochemical cycling in the upper 1,000 meters of the ocean, continental margin carbon dynamics, and air-sea gas exchange.

Focused process studies in the North Atlantic, North Pacific, and along the continental margins of those basins, including inputs from rivers and estuaries, are needed in the next several years to provide independent constraints on quantification of the Northern Hemisphere carbon sink, enable designation of sources and source dynamics, and improve estimation of the retention capability of the sinks (NACP, 2002).

It is anticipated that in 5 to 10 years, an intensive program of research will be needed to resolve uncertainties about the sensitivity to climate change of the physical, chemical, and biological factors regulating carbon fluxes in the Southern Ocean. The specific objectives of this Southern Ocean Carbon Program will be defined in the next several years as the results of recent research in the Southern Ocean [i.e., Joint Global Ocean Flux Study (JGOFS) and World Ocean Circulation Experiment (WOCE)] are synthesized and become available, carbon cycle models are improved, and new enabling technologies are developed.

Milestones, Products, and Payoffs

- Quantification of temporal changes in the global ocean inventories of anthropogenic carbon and related biogeochemical constituents [2-4 years].
- Estimates of the interannual variability in the regional- and basin-scale air-sea CO_2 fluxes for the North Atlantic and North Pacific based on *in situ* measurements, remote sensing, and data assimilation [2-4 years].
- Greater understanding of the role of nutrients and trace metals, phytoplankton functional groups, primary productivity, and subsurface transport and dynamics in carbon export to the deep sea [2-4 years].
- Improved models of ocean biogeochemical processes based on linkages with ocean observations from repeat transects and time-series measurements [2-4 years].
- Observational and modeling constraints on ocean carbon dynamics, land-ocean exchange, and air-sea fluxes for the continental margin regions surrounding North America [beyond 4 years].
- Quantification of global air-sea fluxes of CO_2, lateral ocean carbon transport, delivery of carbon from the land to the ocean, particle fluxes and export rates, and the spatial distribution of carbon in the ocean on seasonal to interannual time scales using remote and *in situ* measurements and data assimilation models [beyond 4 years]. These products will be important inputs for the Climate Variability and Change and Modeling research elements.
- Models of ocean uptake of carbon that integrate biogeochemistry, ocean circulation, and marine ecosystem responses [beyond 4 years]. These models will be important inputs for the Climate Variability and Change and Modeling research elements.
- Estimates of the climate sensitivity and potential feedbacks to climate change of carbon cycling processes in the Southern Ocean [beyond 4 years].

This research will quantify the capacity of the oceans to absorb fossil-fuel CO_2 and sequester carbon through export to the deep sea. Scientific information will be provided on the potential for large feedbacks to the climate system.

Question 7.3: What are the effects on carbon sources and sinks of past, present, and future land-use change and resource management practices at local, regional, and global scales?

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.

Currently, terrestrial ecosystems offset only a modest fraction of fossil-fuel emissions, but deliberate management options offer the potential to achieve additional carbon storage (IPCC, 2000a, 2001a). Utilizing terrestrial carbon sequestration as a near-term option for reducing the buildup of atmospheric greenhouse gases requires an improved understanding of the role of land use and management in the carbon cycle.

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, at local to continental scales, affect carbon stored in terrestrial ecosystems and durable products?
- How do social, political, and economic forces influence decisions regarding land use and resource management, and how might changes in these forces affect the carbon cycle?

Research Needs

Continued monitoring of carbon fluxes and storage (in soil, litter, root systems, vegetation, forest products, woody debris, and sediments) and their response to land-use changes, nutrient inputs, and resource management practices will be required to accurately quantify the role of land-cover and land-use change in the global carbon cycle. 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 are needed to provide an essential foundation of ecosystem monitoring data. Carbon cycle research will require close collaborations with national and international operational resource management and inventory programs to ensure the availability of reliable long-term observations of ecological processes, environmental changes and impacts, and treatment effects. Continued satellite land-cover data products and new remote-sensing estimates of aboveground biomass will be needed. Process studies linked with observations and long-term manipulative experiments will be required to identify cause-and-effect relationships and evaluate interactions with other biogeochemical cycles (e.g., the nitrogen cycle and effects on nitrous oxide emissions).

Research in this area will require inputs from the Land-Use/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. There is also an urgent need for improved understanding of the processes of land-use change and the impacts of environmental and resource management decisions. 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. Thus, collaborations with social scientists and inputs on the social and economic drivers of land-use change from the Land-Use/Land-Cover Change research element will be necessary.

Milestones, Products, and Payoffs

- Database of agricultural management effects on carbon emissions and sequestration in the United States [2-4 years].
- Evaluation of the effects of land-cover and land-use change and disturbance (e.g., fire, erosion) on carbon sources and sinks and the fate of carbon in selected ecosystems (e.g., in Amazonia [2-4 years], northern Eurasia [4 years], and the pan-tropics [beyond 4 years]). This product will be developed in collaboration with the Land-Use/Land-Cover Change research element.
- Quantification of the effects of different land-use changes and management practices on biomass and soil carbon storage and release and their costs [beyond 4 years]. These results will be an important input for the Decision Support element.
- Analysis of the effects of historical and contemporary land-use on carbon storage and release across environmental gradients [beyond 4 years]. This product will be developed in collaboration with the Land-Use/Land-Cover Change research element.
- Linked ecosystem, resource management, and human dimensions models that enable scientific evaluation of effects on carbon sequestration in a context of other management concerns such as market prices, land allocation decisions, and consumer and producer welfare [beyond 4 years]. These models will be developed in collaboration with the Human Contributions and Responses, Land-Use/Land-Cover Change, and Ecosystems research elements. They will provide important inputs for the Decision Support element.

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 for near-term carbon management.

Question 7.4: How do global terrestrial, oceanic, and atmospheric carbon sources and sinks change on seasonal to centennial time scales, and how can this knowledge be integrated to quantify and explain annual global carbon budgets?

State of Knowledge

There is a growing realization that the carbon cycle can only be understood as an integrated global system. It is necessary to study individual components of the carbon cycle (e.g., North America, the world's oceans, ecosystems experiencing changes in land use), but additional attention must be devoted to integrating the results of such studies and placing them in a global context. Many of the most important advances over the last decade involved new combinations of data and models for components of the Earth's carbon cycle to provide valuable understanding of, and constraints on, carbon sources and sinks in other components. Estimates of regional ocean sources and sinks can now be used in combination with atmospheric data to constrain estimates of terrestrial carbon sinks. 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 (CCWG, 1999).

Inverse modeling techniques are approaching continental-scale resolution of sources and sinks, but with significant uncertainties due to sparse input data and the limitations of atmospheric transport models. For much of the world, CO_2 emissions are calculated from national reports of fossil-fuel usage; these country-level statistics are not adequately resolved spatially for many scientific studies and independent validation information is not available. 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 (IPCC, 2000a, 2001a). New remote-sensing observations have engendered a new appreciation for the significant spatial and temporal variability of primary productivity in Earth's ecosystems (FAO, 2002; Ocean Theme Team, 2001).

Illustrative Research Questions

- What are the current state of and trends in the global carbon cycle?
- What natural processes and human activities control carbon emissions and uptake around the world, and how are they changing?
- 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, standardization, management, analysis, and reporting of relevant global carbon monitoring and inventory data; in the elucidation of carbon cycling processes; and in the development of improved process models, interactive carbon-climate models, and, ultimately, Earth system models. New *in situ* and space-based observational capabilities will be needed (FAO, 2002; Ocean Theme Team, 2001). Measurements of atmospheric carbon isotopic signatures and new approaches for deriving or measuring fossil-fuel emissions at higher spatial resolution (i.e., at least 100 km) will be needed to better understand global fossil-fuel emissions. Process studies must focus on characterizing key controls as they vary around the world (e.g., land-use history, ecosystem disturbance regimes, nutrients, climatic variability and change, ocean circulation, resource and land management actions) and on explaining changes in the growth rates of atmospheric CO_2, CH_4, and other greenhouse gases (the effects of black carbon aerosols on the global radiation balance are addressed by the Atmospheric Composition research element).

Improving models will require development of innovative new assimilation and modeling techniques and rigorous testing, evaluation, and periodic intercomparison. Climatic and hydrological data products (e.g., precipitation, soil moisture, surface temperature, sea surface winds, salinity) from the Water Cycle and Climate Variability and Change research elements will be required as inputs for these models. Activities to secure enhanced measurements of atmospheric CO_2, CH_4, other important carbon-containing greenhouse gases, carbon monoxide, and related tracers will need to be coordinated with the Atmospheric Composition research element. Joint improvement of land-atmosphere exchange and atmospheric transport models with the Water Cycle, Atmospheric Composition, and Ecosystems research elements will be required. The Carbon Cycle science program will need to collaborate with all CCSP research elements to assemble, merge, and integrate carbon, biogeochemical, physical, and socioeconomic information for comprehensive reporting on the state of the global carbon cycle. Continued international cooperation will be necessary to integrate results and ensure widespread utility.

Milestones, Products, and Payoffs

- U.S. contributions to an international carbon observing system, including measurements of carbon storage and fluxes, complementary environmental data, and assessment of the current quality of measurements [ongoing; less than 2 years for enhancements]. Some of these will be the systematic climate quality observations needed for the CCRI.
- Global, synoptic data products from satellite remote sensing documenting changes in terrestrial and marine primary productivity, biomass, vegetation structure, land cover, and atmospheric column CO_2 [all but CO_2, ongoing; CO_2, beyond 4 years].
- Global maps of carbon stocks derived from model-based analysis of actual land cover [1-km resolution, 2 years; 30-m resolution, beyond 4 years].
- Identification and quantification of the processes controlling soil carbon storage and loss and global CO_2 exchange among the land, ocean, and atmosphere [2-4 years]. Aspects related to intercontinental transport of carbon-containing trace gases will be addressed in collaboration with the Atmospheric Composition research element.
- Identification of the processes controlling carbon sources and sinks through multi-factor manipulative experiments, studies of disturbance, and integration of decision sciences and risk management studies [beyond 4 years].
- Interactive global climate-carbon cycle models that explore the coupling and feedbacks between the physical and biogeochemical systems [2-4 years].
- First *State of the Global Carbon Cycle* report and balanced global carbon budget [beyond 4 years]. These products will be important inputs for the Decision Support element.

Policymakers and resource managers will be provided with consistent, integrated, and quantitative information on global carbon sources and sinks that can be used in worldwide carbon accounting and for evaluating and verifying 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 decision support systems.

Question 7.5: What will be the future atmospheric concentrations of carbon dioxide, methane, and other carbon-containing greenhouse gases, and how will terrestrial and marine carbon sources and sinks change in the future?

State of Knowledge

Geological and paleoclimatic records indicate that major changes in carbon cycle dynamics have occurred in the past. These changes have been attributed to a variety of feedbacks, non-linear responses, threshold effects, or rare events. For example, there is evidence that huge, near-instantaneous releases of CH_4, very likely from clathrate (CH_4 hydrate) deposits, have affected the climate system in the past. Changes in the ocean's thermohaline circulation may have caused large changes in ocean CO_2 uptake. Failure to consider such possibilities in model projections could result in large over- or under-estimates of future atmospheric carbon concentrations, with consequent implications for policy scenarios (IPCC, 2001a).

Understanding of how carbon cycling may change in response to conditions significantly different from those of the present can be achieved through three complementary approaches: (1) Paleoclimatic and paleoecological information is used to refine our understanding of the processes controlling carbon cycling under past conditions; (2) analogs of future states are employed in manipulative experiments to observe and quantify the behavior of the system under new combinations of conditions; and (3) models (both inverse and forward) are used to simulate future system behavior based on a set of assumed initial conditions and hypothesized system interactions.

Several different types of carbon models are available, but most lack complete integration of all components, interactive coupling, ability to portray rare events or abrupt transitions, 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 (IPCC, 2001a). Current models are less useful for projecting future CH_4 conditions, primarily because sufficient measurements and process understanding are lacking.

Illustrative Research Questions

- How will the distribution, strength, and dynamics of global carbon sources and sinks change in the next few decades and centuries?
- What are the processes that control the responses of terrestrial and marine carbon sources and sinks 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?
- What are the important land use-climate-ocean-carbon cycle interactions and feedbacks? Which of these are most sensitive to climate change and/or have the potential to lead to anomalous responses?

Research Needs

Accurate projections of future atmospheric CO_2 and CH_4 levels are essential for calculating radiative forcings in models that project changes in climate and their impact on the sustainability of natural resources and human populations (NRC, 2001a). Advances will require a combination of observations, manipulative experiments, and synthesis via models enabled by increases in computational capabilities. Paleoecological and paleoclimatic studies will be needed to provide insight into the magnitude and mechanisms of past changes and the potential for abrupt changes in atmospheric levels of CH_4 or CO_2. Manipulative experiments will be needed to understand physiological acclimation to enhanced CO_2 levels, effects on processes that influence feedbacks to the climate system (e.g., nitrous oxide production, evapotranspiration, melting of permafrost), and the integrated effects of changes in multiple, interacting environmental factors.

Modeling activities will need to 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, human activities, and the climate system. Collaborations with the Ecosystems research element on processes of ecosystem change and nitrogen cycling and with the Atmospheric Composition research element on future atmospheric greenhouse gas composition will be essential. Modeling of future carbon conditions will require inputs on future human actions and responses (including changes in energy consumption, land use and management, technology utilization, and adaptation and mitigation practices) from the Human Contributions and Responses and Land-Use/Land-Cover Change research elements and from the CCTP.

Milestones, Products, and Payoffs

- Synthesis of whole ecosystem response to increasing atmospheric CO_2 concentrations, and changes in temperature, precipitation, and other factors (e.g., iron fertilization for the ocean, nitrogen fertilization for terrestrial ecosystems) based on multi-factor experimental manipulation studies [2-4 years]. This synthesis will be developed in collaboration with the Ecosystems research element.
- Advanced carbon cycle models that incorporate improved parameterizations based on data from manipulative experiments, soil carbon transformation studies, and paleoclimatic and paleoecological studies [beyond 4 years].
- Carbon models that include the long-term effects of land use [2-4 years].
- Advanced carbon models able to simulate interannual variability at ecosystem, landscape, and ocean basin scales for selected areas [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 models that address radiative forcing and the potential for abrupt change [beyond 4 years]. This product will be developed in collaboration with the Atmospheric Composition research element.
- Evaluation of the potential for dramatic changes in carbon storage and fluxes due to changes in climate, atmospheric composition, ecosystem disturbance, ocean circulation, and land-use change, and characterization of potential feedbacks to the climate system [beyond 4 years]. This information will provide important inputs to the Climate Variability and Change and Modeling research elements.
- Improved projections of climate change forcings (i.e., atmospheric CO_2 and CH_4 concentrations) and quantification of dynamic feedbacks among the carbon cycle, human actions, and the climate system, with better estimates of errors and sources of uncertainty, from prognostic models [beyond 4 years]. This information will provide important inputs to the Climate Variability and Change, Modeling, and Land-Use/Land-Cover Change research elements and will be of use to the Ecosystems research element for designing and interpreting ecosystem experiments.

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 and analysis of impacts on ecosystems. Both will aid in improving model projections of future climate change.

Question 7.6: How will the Earth system, and its different components, respond to various options 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 economic consequences of reducing emissions, technological options, resultant impacts on natural and human systems, and the overall costs and economic viability of carbon management approaches create an imperative for better scientific information to inform decisionmaking. Current interest in carbon sequestration centers on land management practices that enhance the storage of carbon in soils and biomass (see Figure 7-5), fertilization of the ocean via iron inputs that enhance biological uptake of carbon, and direct CO_2 injection into the deep sea or geological formations. Presently, there is limited scientific information to evaluate the full range of impacts of these various carbon management strategies. Little is known about the long-term efficacy of new management practices for enhancing carbon sequestration or reducing emissions or how such practices will affect components of the Earth system (NRC, 1999a,c). Basic research is needed to assess new management practices, their feasibility and effectiveness in keeping carbon out of the atmosphere on centennial time scales, and their potential environmental consequences or benefits. This research element is tightly linked to the CCTP, which focuses on engineered technologies, carbon offsets, and economic systems.

Illustrative Research Questions

- What is the scientific basis for mitigation strategies involving management of carbon on the land and in the ocean, and how can we enhance and manage long-lived carbon sinks to sequester carbon?
- What are potential magnitudes, mechanisms, and longevity of carbon sequestration by terrestrial and marine systems?

- How will elevated atmospheric CO_2, climatic variability and change, and other environmental factors and changes (such as air, water, and land pollution; natural disturbances; and human activities) 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

Field studies, manipulative experiments, and model investigations will be needed to evaluate the effectiveness of designed management approaches (e.g., emissions reductions, sequestration through manipulation of biological systems, engineered sequestration) to manipulate carbon in the ocean, land, and atmosphere and to assess their impacts on natural and human systems. Approaches for establishing a baseline against which to measure change will be required as will be methods for distinguishing natural system variability from the effects of particular human actions. New monitoring techniques and strategies to measure the short- and long-term efficacy of carbon management activities will be needed, including reliable reference materials that are available to the international community. Experiments and process studies also will be needed to evaluate the likelihood of unintended environmental consequences resulting from enhanced carbon sequestration or emissions reductions practices as well as the full cost of such approaches.

Research on the scientific underpinning for carbon management will require coordination with the Ecosystems research element and the CCTP as well as public and private programs responsible for developing and/or implementing carbon management. It is expected that, whenever possible, field and experimental studies will be conducted in collaboration with existing carbon management projects. Inputs from the social sciences will be needed to characterize societal actions and responses. Models will be needed to incorporate understanding of basic processes into evaluation of natural and enhanced mechanisms of carbon sequestration and to assess the economics of direct CO_2 injection in the ocean and carbon management practices in the agricultural and forestry sectors. Research is needed to support assessments of carbon sequestration and emissions reduction potentials, comprehensive accounting of carbon stocks and fluxes, decisionmaking processes that involve multiple land management scenarios, approaches for calculating net carbon emissions intensity, and verification of the reports required by international agreements.

Milestones, Products, and Payoffs

- Evaluation of the biophysical potential of U.S. ecosystems to sequester carbon [selected regions, 2 years; United States, 4 years] and assessment of carbon sequestration management practices in crops and grazing systems [2-4 years].
- Monitoring techniques and strategies to improve quantitative measurement of the efficacy of carbon management activities: from new *in situ* and existing satellite capabilities [2-4 years] and from new satellite capabilities [beyond 4 years]. This will be an important input for the Decision Support element.
- Identification of the effects of enhanced nutrient availability on carbon uptake in the oceans and on land and of elevated CO_2 on

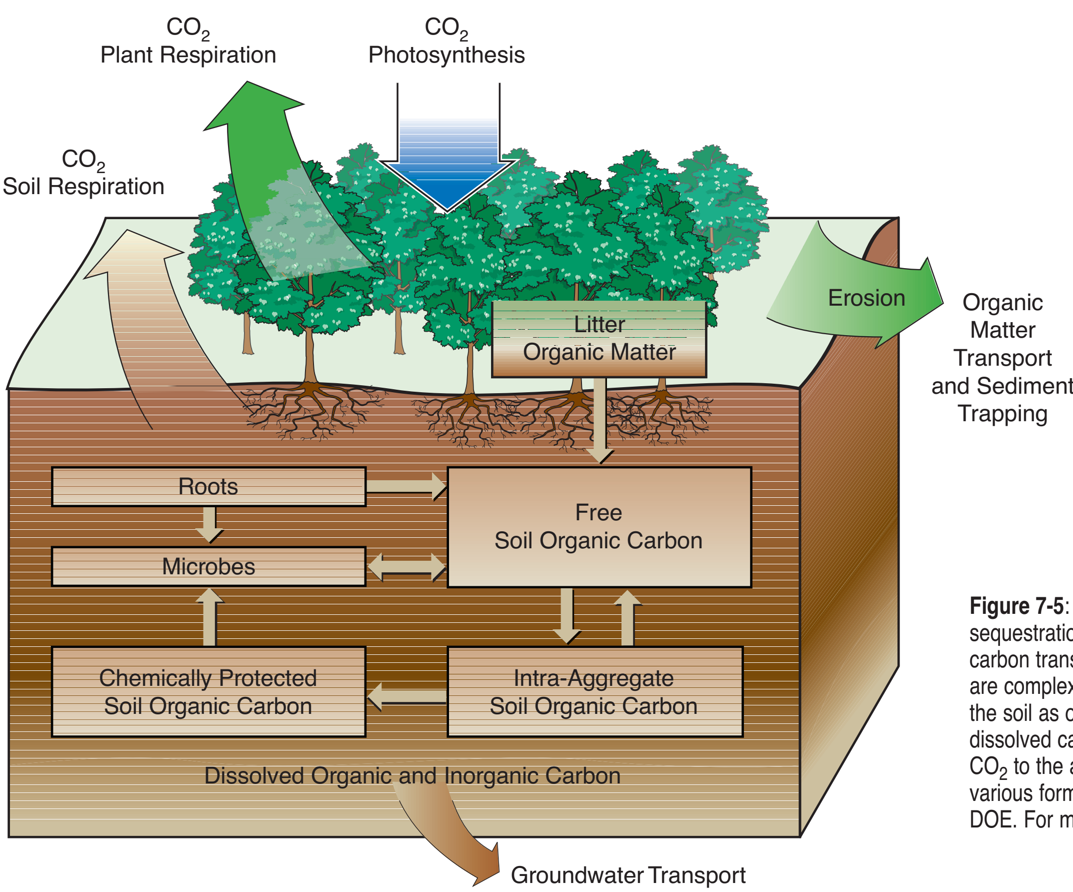

Figure 7-5: Soil processes influence carbon sequestration and transport. The dynamics of carbon transformations and transport in soil are complex and can result in sequestration in the soil as organic matter or in groundwater as dissolved carbonates, increased emissions of CO_2 to the atmosphere, or export of carbon in various forms into aquatic systems. Source: DOE. For more information, see Annex C.

physiological processes and carbon allocation [beyond 4 years]. The terrestrial product will be developed in collaboration with the Ecosystems research element.
- Evaluation of the environmental effects of mitigation options that involve reduction or prevention of greenhouse gas emissions [beyond 4 years]. This product will be developed in collaboration with the Ecosystems research element.
- Analysis of options for science-based carbon management decisions and deployment by landowners [beyond 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. It will provide scientific information for evaluating the effects of actions that change emissions. 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, for full carbon accounting, and for evaluating compliance with international agreements.

National and International Partnerships

Carbon cycle research will depend upon contributions from national programs and projects managed outside of the CCSP and CCTP as well as significant investments by state, tribal, and local governments and the private sector. Priorities for cooperative partnerships are: (1) coordination with long-term ecological research and monitoring programs; (2) collaboration with agricultural, forest, and soil inventories; (3) coordination with the National Oceanographic Partnership Program (NOPP); and (4) collaboration with carbon sequestration and emissions reduction projects supported by governments, non-governmental organizations, and industry. Partnerships with established data repositories and information systems will be needed to ensure access to required data. Cooperation with programs that provide national computational infrastructure will be essential for advances in carbon cycle and climate system modeling. These partnerships will be accomplished, when feasible, through joint planning and coordinated implementation with all participants.

International cooperation will be necessary to integrate scientific results from around the world and ensure widespread utility of *State of the Carbon Cycle* reports and model projections. Close cooperation with Canada and Mexico under the NACP will be important to the success of the program. The United States will depend upon observational networks and field-based carbon programs in Europe (e.g., CarboEurope) and Asia to contribute to an overall understanding of the Northern Hemisphere carbon sink. Partnerships are anticipated with the Integrated Global Observing Strategy-Partnership (IGOS-P) and the global observing system programs [the Global Terrestrial Observing System (GTOS), the Global Ocean Observing System (GOOS), and the Global Climate Observing System (GCOS)] in securing the global observations needed to support carbon cycle modeling and projections of future atmospheric concentrations of CO_2 and CH_4 (FAO, 2002; GOOS, 2002; Ocean Theme Team, 2001). Coordination to establish common standards and measurement protocols and means of interrelating measurements will be a priority.

Interactions with, and contributions to, the joint Global Carbon Project (Global Carbon Project, 2003) of the International Geosphere-Biosphere Programme (IGBP), the International Human Dimensions Programme (IHDP), and the World Climate Research Programme (WCRP) will be essential for scientific interpretation of results from around the world and global-scale integration. CCSP carbon cycle research will contribute to bilateral activities of the Administration by promoting cooperative research on carbon cycle science. Results of CCSP carbon cycle research are anticipated to contribute substantially to future international assessments, especially Intergovernmental Panel on Climate Change (IPCC) assessments and the Millennium Ecosystem Assessment (MA Secretariat, 2002).

CHAPTER 7 AUTHORS

Lead Authors

Diane E. Wickland, NASA
Roger Dahlman, DOE
Jessica Orrego, CCSPO
Richard A. Birdsey, USDA
Paula Bontempi, NASA
Marilyn Buford, 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
Bryce Stokes, USDA
Kathy Tedesco, NOAA
Charles Trees, NASA

Contributors

Enriqueta Barrera, NSF
Cliff Hickman, USDA
Carol Jones, USDA
Steven Shafer, USDA
Michael Verkouteren, NIST