DRAFT WHITE PAPER:

CARBON CYCLE

In support of Chapter 9 of the

Strategic Plan
for the
Climate Change Science Program

Draft dated 26 November 2002

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Preface

On 11 November 2002, the US Climate Change Science Program issued a discussion draft of its *Strategic Plan*. The strategy for each major area of the program is summarized in specific chapters of the draft plan, and for four chapters is described in greater detail in white papers. The white papers, including this one focused on the carbon cycle, represent the views of the authors and are not statements of policy or findings of the United States Government or its Departments/Agencies. They are intended to support discussion during the US Climate Change Science Program Planning Workshop for Scientists and Stakeholders being held in Washington, DC on December 3 – 5, 2002.

Both the chapters of the plan and the white papers should be considered drafts.

Comments on the chapters of the draft *Strategic Plan* may be provided during the USCCSP Planning Workshop on December 3 – 5, 2002, and during a subsequent public comment period extending to January 13, 2003. The chapters of the *Strategic Plan* will be subject to substantial revision based on these comments and on independent review by the National Academy of Sciences. 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. Information about the Workshop and opportunities for written comment is available on the web site www.climatescience.gov.

Comments that are specific to this white paper – and that are not already conveyed through comments on the related chapter of the plan – should be directed to: Ms. Jessica Orrego, Climate Change Science Program Office [jorrego@usgcrp.gov]

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Introduction

Carbon is important as the basis for the food and fiber that sustain and shelter human populations, as the primary energy source that fuels human economies, and as a major contributor to the planetary greenhouse effect and potential climate change. Carbon dioxide (CO_2) and methane (CH_4) are important greenhouse gases; they absorb heat radiation from the surface, thus warming the atmosphere and radiating heat back to the surface. CO_2 and CH_4 concentrations in the atmosphere have been increasing and are now higher than they have been for over 400,000 years. Use of fossil fuels, land clearing, and other human activities over the past 150 years are the cause of most of this increase (NRC, 2001; IPCC, 2001). Concern has been growing that these increases in atmospheric CO_2 and CH_4 are enhancing the greenhouse effect and could lead to potentially disruptive changes in the Earth's climate and ecological systems.

There is considerable uncertainty in our present understanding of how the climate system reacts to emissions of greenhouse gases (NRC, 2001). For example, recent model projections indicate that carbon cycle feedbacks to climate introduce an uncertainty of a factor of two (e.g., about 2° K difference for the year 2100) in global warming projections (Cox et al., 2000; Friedlingstein et al., 2001). Accurate information is needed about how atmospheric concentrations of CO_2 and CH_4 might change, the processes that control those changes, and how interactions between the climate system and the carbon cycle may influence future climate sensitivity and change. The ability to project future climate change, and to accurately model future forcings and feedbacks, ultimately depends on accurate knowledge of how carbon cycle processes regulate atmospheric abundance of CO_2 and CH_4.

The atmospheric concentration of CO_2 has increased by ~30% since 1750. Only about half of the CO_2 released into the atmosphere by human activity (i.e., anthropogenic CO_2 released by combustion of fossil and biomass fuels and by land use changes) currently resides in the atmosphere. There is compelling evidence that the other half has been taken up by plants on land and in the ocean through photosynthesis and by chemical processes in the oceans. Terrestrial ecosystems and the ocean are thus sinks for the so-called “excess,” anthropogenic CO_2. Initial attempts to locate and quantify these sinks and to balance the global carbon budget (using mass balance approaches accounting for known changes in sources and sinks) resulted in a large imbalance, the so-called "missing" or inferred sink (IPCC, 1995). More recent attempts, taking advantage of improved observational and modeling techniques, have ascribed this imbalance to a large Northern Hemisphere terrestrial sink (IPCC, 2001). However, its nature, location and partitioning across Northern Hemisphere terrestrial ecosystems has yet to be resolved.

The atmospheric concentration of CH_4 has increased by ~150% since 1750. Its annual growth rate slowed and became more variable in the 1990’s, compared with the 1980’s, but we do not understand the cause. It is possible that changes in wetlands and/or their hydrologic regimes, permafrost degradation and warming of northern peatlands, land degradation in the moist tropics, increased animal production throughout the world, changes in landfills and/or their management, changes in atmospheric hydroxide radical concentrations, or changes in the oxidative capacity of soils could play a role. The high variability of CH_4 emissions in both space and time has made analysis and global synthesis of source and sink strengths exceedingly difficult (IPCC, 2001).

The efficiency of sinks for carbon storage around the planet varies from year to year and from decade to decade, caused by a variety of mechanisms only partly understood (Keeling et al., 1995). This variability and possible changes in future storage must be better understood if we are to improve our predictive capacity for future atmospheric CO_2 and CH_4 levels. Future atmospheric concentrations of these greenhouse gases will depend on trends in natural and human-caused emissions, changes in land use and management, the capacity of terrestrial and marine sinks to absorb and retain CO_2, and the capacity of the atmosphere and soils to oxidize CH_4.

Decision makers searching for options to stabilize concentrations of greenhouse gases in the atmosphere are faced with two broad approaches for controlling atmospheric carbon concentrations at a level that would prevent dangerous interference in the climate system (which has not yet been determined): 1) reduction of carbon emissions at their source – either through reduced burning of fossil fuels or reducing deforestation; and/or 2) enhanced sequestration of carbon -- either through enhancement of biospheric carbon storage processes or through engineering solutions to inject carbon into the deep ocean or underground geologic formations. Elevated atmospheric CO_2 concentrations, additions of nutrients, and changes in resource management practices can significantly enhance carbon sinks (Walker et al., 1999). Engineering approaches for carbon sequestration provide additional options to reduce the rate of increase of atmospheric greenhouse gas concentrations. However, uncertainties remain about how much additional carbon storage can be achieved, the efficacy and longevity of carbon sequestration approaches, whether unintended environmental consequences would result, and how vulnerable or resilient the global carbon cycle is to such manipulations. Successful carbon management strategies will require solid scientific information on 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.

Knowledge of the carbon cycle, especially biological productivity, is also essential for effective natural resource management. Concerns have been raised about the long-term sustainability of productivity and ecosystem goods and services due to, for example, soil erosion and degradation, pollution, and over-exploitation of resources. Conversely, certain environmental changes, such as CO_2 enrichment, nutrient deposition, and a lengthening growing season, have the potential to enhance productivity (Walker et al., 1999). However, enhancements in productivity may lead to new concerns (e.g., stimulated weed growth, eutrophication of lakes and waterways, reduced forage quality due to greater lignin content, and inhibited growth of coral reefs). More information is needed on the vulnerability and resilience of production systems in order to manage them sustainably under environmental change and increasing human demands, especially those related to changes in the carbon cycle and human actions to manage carbon in the environment.

Scientific progress over the past decade is enabling a new level of integrated scientific understanding of the carbon cycle that is directly relevant to these important societal needs (Sarmiento and Wofsy, 1999). 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 U.S. 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 carbon cycle will be motivated by 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?**

Specific research questions that will be addressed in support of these two overarching questions are covered in the following sections; they identify research issues of high priority and potential payoff for the next ten years. Five of these questions derive from and substantially match the program goals recommended in *A U.S. Carbon Cycle Science Plan* (Sarmiento and Wofsy, 1999); a sixth question (Question 3 below) has been added to emphasize the need for global-scale integration. It is important to emphasize that carbon cycling is an integrated Earth system process and no one of the six questions can be addressed in isolation from the others – or without contributions from and interactions with the other research elements of the U.S. *Climate Change Science Program* (*CCSP*) and the international scientific community. Carbon cycle Questions 1-2 focus on regions of the world where there are large uncertainties in the magnitude and geographic distribution of carbon sinks and where potential payoffs for a U.S. research contribution seem high (i.e., North America's contribution to the Northern Hemisphere sink and the global oceans -- especially the Southern Ocean). Question 3 emphasizes the need for a global-scale integration of carbon cycle knowledge as well as the importance of being prepared to address changes in carbon source/sink strength or dynamics in all parts of the world. Carbon cycle Questions 4-6 address special and important challenges for advancing our understanding of the global carbon cycle in a changing world. In particular, land cover and land use changes are playing an important role in perturbing the carbon cycle, but neither the historical impacts nor the magnitude and consequences of current impacts are yet fully characterized. Carbon cycle Question 4 will need to be addressed in full partnership with the *Land Use/Land Cover Change* element of *CCSP*. Question 5 focuses on providing information about future changes in carbon cycling needed to improve climate models and their projections, including improved parameterizations of process controls and model projections of future concentrations of CO_2 and CH_4. Results from research conducted under carbon cycle Questions 1-4 and 6 will be required to address Question 5. Carbon cycle Question 6 focuses on providing the scientific underpinnings for deliberate human management of carbon in the environment; results from Questions 1-4 and the modeling tools developed under Question 5, and close collaboration with the *Ecosystems* element and the *National Climate Change Technology Initiative (NCCTI)*, will be needed to evaluate integrated Earth system responses and assess the efficacy of carbon management for climate change mitigation.

Many of the research activities, research needs, and products and payoffs identified under each question below will be relevant to more than one question; this apparent overlap is necessary and is indicative of the high level of integration sought. A well-coordinated, multidisciplinary, interagency research strategy, bringing together a broad range of needed infrastructure, resources, and expertise, will be essential in providing the scientific information needed to answer these questions. A continuing dialogue with stakeholders, including resource managers, policy makers, and other decision makers, will need to be established and maintained to ensure that desired information is provided in a useful form. The *CCSP* plan for program management and review to achieve the requisite coordination and integration is provided in Chapter 15.

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

Previous estimates of enormous carbon losses from terrestrial ecosystems (Bolin, 1977; Woodwell et al., 1978) have been supplanted by results from a variety of research studies indicating that terrestrial ecosystems have been close to neutral with respect to carbon storage in recent decades. The observed global deforestation appears to have been roughly offset by enhanced carbon uptake (Sarmiento and Wofsy, 1999). There is strong evidence of a current Northern Hemisphere terrestrial sink of 0.6-2.3 Pg of carbon per year (IPCC, 2001). Pacala et al. (2001) estimated the coterminous U.S. carbon sink to be 0.30-0.58 Pg of carbon per year for the period 1980-1989, with apparent consistency between atmosphere- and land-based approaches. 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 management practices, such as fire suppression (Myneni et al., 2001) and reduced and no till agriculture (Lal et al., 1998). Other studies suggest that elevated CO_2, nitrogen deposition, and changes in regional rainfall patterns also play a role (Schimel et al., 2000; Nemani et al, 2002). Atmospheric studies and forest inventory data indicate that the terrestrial sink varies significantly from year to year, but the mechanisms responsible for this variability are not well understood. Current estimates of regional distributions of carbon sources and sinks derived from global atmospheric and oceanic data differ from detailed forest inventory and terrestrial ecosystem model estimates. More accurate and precise understanding of carbon source and sink properties, uncertainties, and variability at the continental scale is needed.

The U.S. and Canada have the observing, research, and modeling infrastructure and capacity largely in place to initiate an integrated analysis of North America's carbon dynamics. And, for the first time, our state of knowledge seems sufficiently mature to balance the continent's carbon budget and to conduct the analyses needed to explain the processes controlling it. At the same time it also should be possible to characterize interannual variability in carbon dynamics and to identify and quantify regional carbon sources and sinks. Major issues that must be addressed are the role of land use, disturbance, and vegetation structure and composition in carbon storage. Also of great importance is the need to determine the potential fertilization effects of CO_2 and nitrogen.

The U.S. *CCSP* has created a structure for coordinating the observational, experimental, analytical, and data management work needed to address the uncertainties, to reduce the errors, and produce a consistent analysis for North America in a North American Carbon Program (NACP). The NACP is a coordinated research effort to 1) develop quantitative scientific knowledge of the emissions and uptake of CO_2, and CH_4, the changes in carbon stocks, and the factors regulating them for North America and adjacent ocean basins, 2) develop the scientific basis for full carbon accounting, and 3) support long-term quantitative measurements of carbon sources and sinks and develop forecasts for future trends (Wofsy and Harriss, 2002). The NACP calls for strengthened collaborations and new partnerships with Canada and Mexico. With corresponding international research projects in Europe and Asia, this research will contribute to improved information on quantities, locations and uncertainties of the Northern Hemisphere carbon sink and the biophysical mechanisms that regulate it. Research on the ocean basins adjacent to North America is noted under carbon cycle Question 1 and elaborated under carbon cycle Question 2.

RESEARCH QUESTIONS

- ***What is the carbon balance of North America and adjacent ocean basins? (see also carbon cycle Question 2)***
- ***How large and variable are North American carbon sources and sinks? What are the geographic patterns of carbon fluxes and changes in carbon stocks?***
- ***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?***
- ***Are there potential "surprises," where carbon sources could increase or carbon sinks disappear?***
- ***How much do North America and adjacent ocean basins contribute to the Northern Hemisphere carbon sink?***

READINESS AND FEASIBILITY

Carbon measurements are being made at a wide variety of sites across North America including DOE's AmeriFlux network, Fluxnet-Canada, and other international FLUXNET sites; USDA's Rangeland network; NOAA's global cooperative air sampling and tall tower networks; the Long-Term Ecological Research (LTER) network; and many other experimental sites. Ongoing studies at these sites are examining the effects of changes in seasonal climate, stability of soil organic carbon, carbon allocation within plants and its transfer from roots to the soil, and decomposition of dead plant material. Also studied are the effects of fire and other forms of disturbance on above- and belowground biomass and the processes controlling the cycling of carbon. Ongoing national forest, rangeland, and soil inventory programs also gather relevant data, which could be further enhanced to improve their usefulness for quantifying carbon stocks.

Continental-scale research using aircraft, tall towers and the AmeriFlux network, all linked via atmospheric transport modeling, will help identify carbon sink strength at regional and local scales. New observations of atmospheric tracers are available to identify and track carbon sources (e.g., carbon monoxide (CO) as a tracer for biomass burning and industrial carbon emissions, sulfur hexafluoride as a proxy for fossil fuel emissions, and radon as an indicator of terrestrial air masses). A variety of airborne remote sensing aircraft and advanced sensors (e.g., digital aerial imagers, radars, and lidars for carbon stock estimates) are available for local-scale observations and surveys.

Satellite time series data, starting in the 1980s, for land cover, vegetation properties, and ocean color have been assembled, and a wide variety of additional, well-calibrated satellite data products (e.g., leaf area index (LAI), fraction of absorbed photosynthetically active radiation(FAPAR), fire occurrence and burned area, phytoplankton fluorescence) are now becoming available from a new generation of satellite remote sensing systems. Of particular relevance are new observations of atmospheric CO and the possibility of retrieving atmospheric column CO_2 and CH_4 from satellite observations.

The NACP has a structured research plan to accurately determine net fluxes of CO_2 and CH_4 into and out of N. America over the next 4-5 years. The plan combines intensive, regional scale studies that are strategically embedded within a long-term measurement network with modeling to diagnose fluxes at the continental scale. Components of the observation program include continuous measurement of CO_2 and CH_4 concentrations and fluxes by ground-based, ocean-based, and aircraft methods plus *in situ* and remote sensing observations of soil, vegetation and sea surface properties. A new generation of diagnostic models will analyze data and deliver well-constrained values for regional and continental fluxes. The initial phase of NACP research involves intensive deployment for 1-2 month intervals of high-performance aircraft capable of advanced measurements over large areas, a dense network of tower-based real-time observations and ground-based remote sensing, and detailed regional ecological characterization of biological processes that regulate carbon exchanges with the atmosphere. One important aspect of this strategy is to use intensive campaigns to formulate long-term observational frameworks and to conduct critical tests of the capability of the long-term observational network to deliver accurate flux determinations for both regions within North America and the continent. Together, the new observation and modeling programs are expected to significantly augment scientific knowledge of the carbon cycle and provide new insights for carbon management.

Research on North American carbon fluxes will be coupled with companion research in Europe and Asia to better evaluate the overall Northern Hemisphere carbon sink. Data and research results from other parts of the world will be needed to help constrain this analysis.

RESEARCH NEEDS

Continued and enhanced NACP research will require multidisciplinary investigation of atmospheric CO_2 and CH_4 concentrations, profiles, and transport; CO_2 and CH_4 fluxes with accompanying biometric measurements at local ecosystem and landscape scales; biomass and soil inventories of carbon in forest, crop, grazing, and range lands and in unmanaged ecosystems; coastal zone carbon processes; and carbon modeling to integrate and assimilate diverse sources of data. Historical land use change and management practices will need to be documented in order to quantify mechanisms and estimate longevity of current carbon storage (see also carbon cycle Question 4 and the *Land Use/Cover Change* element). Fossil fuel use patterns are also required in order to estimate source terms for the carbon balance over North America.

A field program, with intensive campaigns and remote sensing of vegetation productivity and land cover, will be conducted initially at a central location in the U.S., 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/sink dynamics. Priority requirements include:

Observations and monitoring:

- Continued and enhanced CO_2 flux measurements from eddy covariance networks, tall tower networks, air flask collection networks, and atmospheric CO_2 profiling. Expanded research should: 1) address the footprint being measured, advective effects on net CO_2 exchange, and uncertainties about nighttime fluxes; 2) obtain measurements of flux components, especially those associated with belowground processes; 3) evaluate accuracy by comparison with biometric measurements of the carbon balance; 4) develop strategies for estimation of carbon fluxes in complex terrain; and 5) develop a rigorous approach for geographic placement of new flux measurement sites.
- Enhancements to land (forest, grazing and rangeland, crop, soil) inventories and forest health monitoring networks to optimize carbon stock analyses (see also carbon cycle Questions 3, 4, and 6). The limitations of existing databases will guide enhanced data acquisition needed for constructing carbon budgets of the atmosphere; agricultural, grazing, and forest lands; and unmanaged ecosystems.
- Regional analysis of net primary production (NPP), distribution of land cover, and vegetation stress using time-series data from space-based sensors.
- Coastal ocean margin and river monitoring of carbon and nutrients leaving North America in order to determine if these regions are sources or sinks for carbon (see also carbon cycle Question 2).
- Improved meteorological data on time and space scales necessary to track carbon transport in the atmosphere.

Process studies:

- Research on ecosystem mechanisms and controls of CO_2 exchange as a component of NACP field campaigns. Enhanced experimental research on carbon processes and

mechanisms for model parameterizations. Manipulative experiments (e.g., Free Air Carbon Enrichment (FACE) and mesocosm studies) will provide critical data for understanding the processes controlling rates of CO_2 exchange, the magnitude of carbon sinks, and the longevity of carbon sequestered by terrestrial ecosystems (see also carbon cycle Questions 3, 4, 5 and 6). These studies are important for providing half-century forward projections of how ecosystems will process carbon in a world with higher atmospheric CO_2 concentrations and changed climatological conditions.
- Research on the effects of management practices on carbon storage and release (see carbon cycle Question 4 for elaboration).
- Research on mechanisms that control soil respiration.
- Research on coastal ocean processes and carbon export by river systems to determine the fate of carbon in the coastal ocean (see also carbon cycle Question 2).
- Research on mechanisms that influence CO_2 concentrations of air masses traversing North America (see also carbon cycle Question 5).

Modeling:

- Model diagnostic analyses (of land surface data, including soils, topography and hydrology; coastal ocean data; atmospheric data; and carbon flux data) of North American and Northern Hemisphere carbon source-sink dynamics using ecosystem, inverse, and data assimilation modeling approaches.
- Tests of predictions from process-based models of carbon sources and sinks, and tests of the algorithms used to extrapolate results from these models to large scales (see also carbon cycle Question 3).
- Mass-balance and inverse modeling techniques, operating at multiple scales in space and time that produce tightly constrained estimates of net carbon flux tied to realistic high-resolution hour-to-hour weather analyses.

Other:

- Improvements in databases for fossil fuel use and land use/land cover (see also carbon cycle Question 4) (joint with *Human Contributions and Responses* and *Land Use/Land Cover Change* elements, respectively).
- Development of remote sensing technologies for measurement of atmospheric CO_2, CH_4, and CO (to be used as a tracer) and for above ground biomass. New satellite data sets are a long-term requirement. There are near-term needs for airborne instruments to make such measurements in support of NACP's intensive field campaigns as well as to assess the technologies being developed for space.
- Development of *in situ* sensors and sampling protocols for robust, accurate, and easy to make measurements of CO_2, and CH_4.

PRODUCTS AND PAYOFFS

- Prototype State of North American Carbon Report (2 years).

- Quantitative carbon budget analyses for selected regions of the U.S., including documentation of atmospheric CO_2 trends and net exchange of CO_2 (2 years) and an analysis of regional carbon sources and sinks and prospects for carbon management in U.S. managed systems (2-4 years).
- Quantitative measures of atmospheric CO_2 and CH_4 concentrations in locations that are under-sampled with respect to global source/sink analysis requirements (2-4 years).
- Carbon cycle models focused on North America (2-4 years): with improved physical controls and characterization of respiration and improved portrayal of fire and other forms of disturbance, and the first carbon cycle models using data assimilation approaches (2-4 years).
- Improved quantitative documentation of carbon fluxes for North American ecosystems from enhanced observational networks (flux, atmospheric CO_2 concentration) (2-4 years) and satellites (> 4years), and integrated flux estimates for North America, with regional specificity and uncertainties that are both reduced and well quantified (> 4 years).
- Landscape-scale estimates of carbon stocks in managed agricultural, forest, and grazing systems and in unmanaged ecosystems from spatially resolved carbon inventory and remote sensing data (> 4 years) and improved quantitative documentation at regional scales of aboveground biomass and total carbon stocks (selected regions - 2-4 years; North America - > 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).
- Improved knowledge of soil carbon storage and fluxes using new measurement technologies and modeling approaches (> 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. Experimental data will be used to improve models, to facilitate scaling in space and in time, and to evaluate approaches to managed carbon sequestration. Analysis of continental and Northern Hemispheric sink properties will be evaluated using inverse modeling approaches. These analyses will draw on atmospheric, oceanic and terrestrial data, including results from North Atlantic and North Pacific ocean surveys that inventory carbon and measure air-sea fluxes (see carbon cycle Question 2), from terrestrial flux measurements such as from the AmeriFlux and Fluxnet-Canada networks, from continental scale aircraft campaigns, and from atmospheric CO_2 and isotopic monitoring networks that identify location, seasonality and strength of carbon sinks. These inverse methods will also contribute to comprehensive global carbon cycle modeling and analysis. Sustained support of terrestrial carbon cycle modeling will enable integration of results from observations and experiments. More emphasis will be placed on model testing with increasingly rigorous model-data comparisons.

Accurate surface ocean partial pressure of CO_2 (pCO_2) measurements along with spatial and temporal interpolation techniques utilizing remotely sensed products, such as ocean color, surface temperature, and winds, in the North Atlantic and North Pacific will further constrain inverse and other global carbon cycle model analyses of the Northern American carbon sink (see also carbon cycle Question 2). Impacts of fire management and intensive land use/land management on carbon cycling in North America will be evaluated. This includes analysis of the relationship between past changes in management practices and regional patterns of carbon uptake, storage, and release, and estimating likely impacts of future changes in land use and land management on carbon cycling and carbon storage.

These results are prerequisite for planning, implementing and monitoring carbon sequestration practices in North America and as input for evaluating alternative approaches for managing carbon, i.e., for decision support. The outcome of the research will be to provide decision makers with tools to evaluate the consequences of various policy options for the North American component of the carbon cycle. Over time, the accuracy and reliability of information provided to decision makers about the status and trends of carbon in North America will improve and become increasingly useful in policy formulation and resource management.

LINKAGES

The intensive field programs and long-term measurements of the NACP will need to be closely coordinated with the *Atmospheric Composition* element, especially the INTEX airborne campaigns and research on CH_4, with potent benefits flowing in both directions. The NACP will also require strong, mutually beneficial linkages with the *Ecosystems* and *Land Use/Land Cover Change* elements in areas of resource management (forests, agriculture, range and grazing lands) and ecological observations, process studies and manipulative experiments. There is a critical dependency for NACP on quality weather, climate, and hydrological data and models, requiring collaboration with the *Climate Variability and Change* and *Water Cycle* elements. Similarly, in order to understand human-caused emissions and resource management and decision making processes, collaboration with the *Human Contributions and Responses* element will be necessary.

The NACP is intended to be a major component of the emerging international framework for carbon studies (Hibbard et al, 2001; Cihlar et al., 2001). It will be important to strengthen existing collaborations and to develop new partnerships with Canadian and Mexican researchers at both the scientist-to-scientist and agency-to-agency levels to truly answer the NACP questions at a continental scale. Linking with international efforts in the Northern Hemisphere will be essential for resolving the North American contribution to the Northern Hemisphere carbon sink.

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 oceans, covering nearly 70% of the Earth's surface, have a great capacity to absorb CO_2 -- even though short-term uptake rates may be slow. Globally, the net oceanic uptake of carbon is approximately 1.9 Pg per year (IPCC, 2001). However, uncertainties in this estimate remain due to regional variations in ocean uptake, seasonal to interannual variation in nutrient supply, and inadequate representation of coastal margins in models. Evidence from the paleo-record shows that ocean carbon cycling has not been constant through geological time. Changes in climate, such as increased temperature or redistribution of precipitation, may affect ocean circulation and mixing, which in turn may affect the carbon storage capacity of the ocean. Because the physical (e.g., temperature and surface winds), chemical (e.g., the ocean carbonate system and nutrients), and biological (e.g., photosynthesis and ecosystem species composition) factors that drive the partitioning of carbon among planetary reservoirs are climatically linked, the capacity of the oceans to exchange and store atmospheric CO_2 is expected to be affected by future climate change.

There are major aspects to the ocean's role in the global carbon cycle: air-sea CO_2 exchange, carbon flux from the upper ocean to the deep sea, and oceanic carbon storage. In the past few years advances in measurement and analytical techniques have allowed for direct measurement of carbon exchange between the ocean surface and atmosphere and the export of fixed carbon to the deep sea. Progress has been possible not only because of advances in technology, but also because of U.S. interagency and international efforts to coordinate and inter-calibrate carbon measurements made at sea.

Knowledge of air-sea CO_2 exchange is needed to evaluate and predict the extent of the ocean carbon sink. It is estimated on regional or global scale from measurements of surface pCO_2 (the partial pressure of CO_2) data or from space-based observations (i.e., sea surface temperature, wind speed, and sea surface roughness). The exchange of carbon across the air-sea interface is controlled by a complex set of time- and space-varying physical and chemical processes that are difficult to generalize. For example, the flux of CO_2 is proportional to the gas-exchange coefficient, which has been parameterized using a number of wind speed-dependent formulations, each leading to very different estimates of the air-sea CO_2 flux. Measurements from a variety of *in situ* (ships, moorings, towers, drifters, and autonomous vehicles) and remote-sensing (aircraft and satellite) platforms are being applied to better understand this. While satellites provide routine global measurements, substantial algorithm development will be needed to improve the accuracy of derived products for key carbon quantities.

Synthesis of the past decade's high quality, wide coverage carbon system measurements collected in the World Ocean Circulation Experiment / Joint Global Ocean Flux Study (WOCE/JGOFS) Ocean CO_2 survey is currently underway and basin-scale results are complete for the Indian, Pacific, and Atlantic Oceans (Gruber, 1998; Sabine et al., 1997). This global synthesis has provided the most reliable measurement-based estimates available for the oceanic storage of anthropogenic CO_2. These data also will be used to improve model representations of ocean circulation and carbon storage as in the international Ocean Carbon Cycle Model Intercomparison Project (OCMIP) of the IGBP. Global maps of estimated primary productivity are being produced from satellite ocean color observations (Behrenfeld et al., 2001). Existing models of ocean productivity differ by a factor of two, but comparison studies are underway to improve their performance (Campbell et al., 2002).

A number of recent field campaigns that included detailed process studies, have explored the role of biogeochemical processes, such as nutrient dynamics and microbial ecosystem functions, in controlling the temporal variability of carbon fluxes in the North Atlantic, Equatorial Pacific, Arabian Sea and Southern Ocean. Time-series observatories such as the Hawaii Ocean Time-Series (HOTS) and the Bermuda Atlantic Time-Series (BATS) stations have also contributed to these studies. New understanding from process studies is being incorporated into improved models, linking ocean biogeochemical and transport processes with the global carbon cycle.

A new development in understanding the factors controlling carbon cycling is the discovery that iron is a limiting nutrient for major regions of the world's oceans. There have been several iron fertilization experiments conducted over the past decade, and each showed unequivocally that addition of iron to regions replete with major nutrients significantly enhanced biological productivity (e.g., Gervais et al., 2002; Law et al., 2001). The results of this work are contributing significantly to our understanding of important biogeochemical processes that directly affect the global carbon cycle and atmospheric CO_2 concentration.

Carbon cycle models that simulate the distribution of carbon in the ocean are now being tested and their results compared with *in situ* and remotely sensed data. Results from process studies investigating the interaction between the ocean surface and lower atmosphere (e.g., Surface Ocean Lower Atmosphere Study - SOLAS) as well as biological responses to climate forcing are being incorporated into global carbon models. 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.

RESEARCH QUESTIONS

- ***What are the locations and magnitudes of regional ocean carbon sources and sinks?***
    - *How accurately must these sinks be quantified to provide sufficient constraints on the distribution of other global carbon sinks (oceanic and terrestrial)?*
    - *How much does the interannual and decadal variability in oceanic ventilation and regional heat storage change the uptake and partitioning of oceanic and atmospheric carbon?*
    - *How important are coastal margins to carbon pathways on basin to global-scale, at annual, decadal, and centennial time scales?*

What biogeochemical, ecological, and physical processes control uptake and release of carbon in the ocean, and how will these processes change in the future due to elevated atmospheric CO_2 and climate change?

- What are the links between large-scale, low-frequency variations (e.g., North Atlantic Oscillation (NAO) and Pacific Decadal Oscillation (PDO)) and higher *frequency phenomena, which seem to exert strong control on regional to local fluctuations in biogeochemical cycling?*
- *How are ecosystem dynamics and carbon cycling affected by sources of iron from above and below (dust, upwelling, margins, hydrothermal sources)?*
- *How will changes in ocean circulation affect the storage of carbon and will there be any surprises?*
- *How is carbon cycling affected by basin scale differences between nitrogen fixation and denitrification?*
- *What controls the fate of carbon-containing material that leaves the surface euphotic layer where carbon fixation and air-sea exchange occur?*
- *How will variability and trends in climate change affect ecosystem composition, and in turn the export of carbon to the deep ocean?*

READINESS AND FEASIBILITY

Valuable carbon data are currently available from ocean time series (BATS and HOTS) sites; satellite time series of sea surface temperature and ocean color; and frequent measurements of pCO_2 from various measurement platforms. In addition, programs like WOCE and JGOFS have provided great insight and valuable data on ocean biogeochemistry as well as positioned the community to take the next steps. However, the ocean remains seriously under-sampled. These measurements will need to be significantly enhanced if carbon cycling processes in the ocean are to be understood and regional sources and sinks quantified. Significant national and international planning has already taken place to define the observational needs and identify the potential contributors.

The CO_2 Repeat Hydrographic Survey in collaboration with CLIVAR and international partners will be launched in 2003. This survey also will include measurements of anthropogenic CO_2 tracers. There is ongoing collaboration with the U.S. Integrated Coastal Ocean Observing System (I-COOS) to develop a coordinated national network for the measurement and analysis of a common set of oceanographic variables that are needed for many types of research apart from carbon cycle research. In addition, there is an ongoing national and international collaboration to support the intercomparison and merger of ocean color data sets from a variety of national and international satellite instruments in order to provide climate quality long-term data records of phytoplankton biomass and productivity.

RESEARCH NEEDS

Enhanced predictive capability requires an observing strategy for ocean carbon sources and sinks and improved understanding of key processes and their response to variability in climate forcing. Ocean carbon cycle research is still data-limited, especially in terms of documenting seasonal and interannual variability. Nutrient cycling and ecosystem processes, the role of species groups that have similar functions, climate variability, and air-sea CO_2 exchange are all critical factors influencing carbon cycling in the ocean. Incorporation of process understanding in ocean carbon models and recognition of sources of uncertainty are needed to successfully predict future atmospheric CO_2 concentrations. Thus large-scale data acquisition, focused process studies, and model-data integration are key research needs.

The observing strategy should provide data on a regular basis for integration into predictive models and to aid in constraining the terrestrial carbon sink. This strategy must include targeted *in situ* measurements coupled with sustained, systematic satellite observations. A multiple approach strategy for an *in situ* observing network through the international Global Ocean Observing System (GOOS) will be adopted, including observations on dedicated research vessels, ships of opportunity, volunteer observing ships, moorings, drifters, and autonomous vehicles. Improvement of ocean sampling technology is necessary so sampling can occur on broad spatial scales and capture variability on a variety of time scales. Traditional *in situ* sampling at sea has involved research vessels with limited coverage. Recent developments in mooring and autonomous sampling devices have paved the way for a much broader sampling strategy. Development of appropriate autonomous sensors for key carbon system measurements, which can be deployed aboard various platforms, is needed. Algorithm development and improvements in merging models and data to optimize predictive capability will be crucial for high-resolution projections of future global change. Primary production models, air-sea CO_2 exchange, phytoplankton community structure, and models of calcification rates are research areas that will benefit from focused activity in the next 2-5 years. Satellite data intercomparison and merger activities must be continued and expanded to include a broader range of carbon data products. A collaborative effort to improve our ability to estimate air-sea CO_2 flux from remote sensing platforms would enable quantification of ocean CO_2 uptake of at unprecedented spatial and temporal scales.

The role of the coastal zone in the global carbon cycle is yet unclear. It is complex and will require unique sampling approaches and techniques. The coastal zone is where terrestrial and marine processes interact and is characterized by highly episodic events occurring at small temporal and spatial scales. New measurement approaches will be required to monitor biogeochemical variability in the optically complex coastal waters. Frequent, high-resolution observations of small-scale phenomena will be needed.

Focused process studies in the North Atlantic, North Pacific, and along ocean margins of those basins, are needed to quantify the Northern Hemisphere carbon sink and to improve understanding of the mechanisms controlling and magnitudes of carbon exchange among land, sea, and air. In five to ten 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 it. Incorporation of improved process understanding in ocean carbon models and recognition of sources of uncertainty are needed to successfully predict future atmospheric CO_2 concentrations.

The fusion of data and models remains a key issue in oceanography, particularly for biological and biogeochemical models where large-scale data assimilation is still in its infancy. With the expected long-term availability of satellite ocean color imagery and the rapid development of autonomous *in-situ* samplers, sufficient data may be available soon to generate reasonable ocean biogeochemical state estimates, at least for key surface ocean properties (e.g., biomass, productivity, sea surface pCO_2). Progress in this area requires that a number of technical and scientific issues be resolved, especially: 1) determining the time/space scales of biological variability; 2) assessing the tradeoffs between measurements of extensive (e.g., satellite chlorophyll) and intensive (e.g., size class structure; grazing rates) properties; and 3) optimally defining the dynamic relationships among the ecosystem variables such that assimilation of one observable quantity (e.g., chlorophyll) projects onto other, unobserved ecosystem components (e.g., bacterial and zooplankton biomass). Priority research needs include:

Observations and Monitoring:

- Continuation of ocean time series (BATS and HOTS), and continuation and enhancement of *in situ* observations and measurements of air-sea gas exchange and trace gases, and periodic ocean surveys to inventory ocean carbon data from all available classes of measurement platforms.
- Continuation of satellite time series of ocean color and sea-surface temperature data products.
- Development of an enhanced global ocean observing system to monitor key oceanographic properties, such as temperature, salinity, wind speed, current velocity, chlorophyll, mixed layer depth, water clarity, and spectral surface irradiance.
- A new program of cruise-based observations and moored sensor deployments to determine how carbon fluxes and ecosystem structure respond to physical variability on ENSO, PDO and NAO time scales, and to improve projections of climatic effects on the carbon cycle.
- New, high-resolution remote sensing observations of coastal oceans.
- Development of seawater standard reference materials and measurement protocols.

Process studies:

- Increased understanding of key biological controls, such as photosynthesis, food webs, nutrient processes (including iron inputs), and photochemical processes and of how they affect carbon dynamics.
- Design and implementation of new process studies to estimate the contribution and interannual variability of the spring phytoplankton bloom (e.g. North Atlantic) to annual carbon storage and to determine the importance of active nutrient transport, nitrogen fixation, eddy dynamics and other processes in the supply of nutrients.
- Establishment of mechanistic relationships between ecosystem structure, carbon fluxes, physical forcing and environmental boundary conditions, incorporating evolving hypotheses concerning linkages to the state of the tropical oceans, as steps

toward understanding the response of biogeochemical systems in the Southern Ocean to climate change.

- Determination of the role of rivers and coastal margins in ocean carbon dynamics; configure a series of ocean margin studies designed to resolve the contribution of continental margin processes to basin scale carbon dynamics (see also carbon cycle Question 1).
- Robust parameterizations (e.g., wind speed, sea surface roughness) for air-sea CO_2 exchange coefficients.

Modeling:

- Improved models incorporating ocean process understanding to reduce uncertainty in projections of future atmospheric CO_2 concentrations. Model advances over the next decade can be expected through the extension and sophistication of techniques to include multi-nutrient limitation, plankton functional groups, more explicit dissolved organic matter/microbial interactions, eddy resolution, and data assimilation approaches.
- Development of models that can ingest results of small process-oriented carbon studies and be extrapolated to larger global scale. Determine whether satellite imagery can serve as the basis for this extrapolation.
- Development of protocols and data standards that can be used to compare various physical and biogeochemical models.
- Development of data assimilation models for ocean carbon cycling. These models should make use of sea surface temperature, advection, ocean color, pCO_2, winds, and atmospheric inversions to produce spatially gridded fluxes on monthly time steps.
- Incorporation of higher spatial and temporal resolution in process driven ocean models.

Other:

- A formal data policy to ensure timely data submission and improved data access and management.
- Development of technology and improved instrumentation for appropriate automated sensors to make key carbon system measurements and that can be deployed aboard various platforms (see also carbon cycle Question 1).

PRODUCTS AND PAYOFFS

- Contributions to the prototype *State of North American Carbon Report* (2 years).
- Quantification and spatial mapping of daily to interannual variability in air-sea CO_2 exchange, phytoplankton biomass, calcite concentrations, and productivity using satellite instruments (2 years).
- Global maps of pCO_2 produced from the Repeat CO_2 Hydrographic Survey as a continuation of the WOCE/JGOFS Ocean CO_2 survey (2-4 years).

- Greater understanding of the role of nutrients (including iron), phytoplankton functional groups, and primary productivity on deep-sea carbon flux and storage, and the incorporation of these processes into models (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 surface ocean on seasonal to interannual time scales using remote and *in situ* measurements, including measurements from newly developed autonomous CO_2 sensors (> 4 years).
- Remote sensing and carbon data assimilation model algorithms to estimate global and regional pCO_2 (> 4 years).
- Models of ocean carbon sequestration and fertilization that incorporate biogeochemistry, ocean circulation, and the potential response of ecosystems (> 4 years).

This research will quantify the capacity of the oceans to absorb anthropogenic CO_2 and remove carbon from the Earth's dynamic reservoirs through export or transport to the deep sea. Uncertainties in the size of the global oceanic carbon sink will be reduced. Information will be provided to help in analyzing the effects of deliberate carbon management approaches for the ocean. The role of continental margins will be quantified with regard to carbon export and storage and their susceptibility to anthropogenic perturbations (e.g., eutrophication, trawling, pollution, sediment deposition, and coastal development).

LINKAGES

To answer the research questions set forth for ocean carbon sources and sinks, U.S. carbon cycle research will need to be conducted in collaboration with the *Atmospheric Composition* element to resolve uncertainties about atmosphere and ocean exchange and interaction. This research will also require collaboration with the *Climate Variability and Change* element to further our understanding of ENSO, PDO, and NAO, and their effects on ocean biogeochemistry and climate. Cooperation with the *Human Contributions and Responses* element will be necessary to understand the human influences on ocean carbon processes, particularly in the coastal zones. Cooperation with the *Ecosystems* element will be essential for understanding ecological and biological controls on carbon cycling and in the conduct of manipulative experiments involving ocean ecosystems. Cooperation with the *CCRI* element on *Observations, Monitoring and Data Management* will be important for coordinated observation strategies and inter-relating data sets to produce climate quality time series.

Cooperation with the National Oceanography Partnership Program (NOPP), a collaboration of fourteen Federal agencies to provide leadership and coordination of national oceanographic research and education programs, will be essential. Areas of interest include operational/routine observations, research observatories, technique development for observations, a forum for exchanging ocean information, and education and outreach. The focus of NOPP is the development of an integrated, sustained ocean observing system for the U.S.

An international effort that addresses many of the ocean carbon cycle issues is the GOOS, which has developed cooperative programs (Global Climate Observing and Coastal Ocean Observing Systems) and research plans. Important links to other important international research programs include WOCE, CLIVAR, JGOFS and IGBP's Land-Ocean Interactions in the Coastal Zone (LOICZ). There are also linkages to CEOS, IGOS-P, the Partnership for Observations of the Global Oceans (POGO) and the International Council of the Exploration of the Sea (ICES).

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 tools and techniques for atmospheric measurement, to distinguish the roles of the ocean and land in carbon uptake (Sarmiento and Wofsy, 1999). These tools and techniques include use of chemical tracers, isotopes, ratios of O_2 to N_2 and improved analysis and modeling capabilities (Baldocchi et al, 1996; Rayner et al., 1998; Keeling et al, 1996; Ciais et al., 1995). Inverse modeling approaches are beginning to allow continental-scale resolution of sources and sinks, but are presently constrained by insufficient input data and the limitations of transport models, and their results rely heavily on initial modeling assumptions (Rayner et al., 2001; Denning et al., 1999; Law et al., 1996; Battle et al., 2000). 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 (Schimel et al., 1997; Randerson et al., 1997; Nemani et al., 2002). New remote sensing observations have engendered a new appreciation for the significant spatial and temporal variability of primary productivity in Earth's ecosystems (Behrenfeld et al., 2001). There is a realization that the carbon cycle can only be studied from an integrated Earth system perspective. This realization is leading to an increased focus on integrated modeling and the use of multiple constraints to evaluate sources and sinks to understand the interactions among terrestrial, oceanic, and atmospheric processes at a planetary scale.

While present understanding indicates that reducing uncertainties associated with the size of the Northern Hemisphere and Southern Ocean carbon sinks will yield the greatest payoff for our overall knowledge of the global carbon balance, it will be important to ensure that carbon sources and sinks in all parts of the world are characterized. There is no guarantee that carbon dynamics and the forces controlling them in other regions will stay the same, and it is prudent to prepare for possible surprises. In fact, we know that land cover and use in the tropics are changing dramatically, that the forces driving those changes are likely to intensify, and that national and international policies and the choices made by people at the local scale can impact the trajectory of change and the overall outcome (Houghton et al., 1996 and 2001; Moran and Brondizio, 1998). We will need to understand the controls on important carbon cycling processes in the terrestrial Southern Hemisphere and be prepared to identify, monitor, and understand future changes in the strength and dynamics of carbon sources and sinks -- wherever they might occur around the world.

Knowledge of the magnitude, distribution, and dynamics of global carbon sources and sinks will also be a prerequisite for improving projections of future atmospheric concentrations of carbon-containing compounds (e.g., CO_2 and CH_4) and future changes in marine and terrestrial carbon sources and sinks (see Carbon Cycle Question 5 below).

RESEARCH QUESTIONS

- ***What is the current state of the global carbon cycle?***
    - *Where are the important carbon sources and sinks, and where are the "hot spots" of change?*
    - *How large are these carbon sources and sinks, and what are the magnitudes of the fluxes among reservoirs?*
    - *How and why are they changing, and what are the rates of change?*
    - *Can we account for all of the sources and sinks and balance the global carbon budget, and what are the errors and remaining uncertainties?*
- ***What natural processes and human activities control carbon emissions and uptake around the world?***
- ***How will changes in climate, atmospheric CO_2 concentrations, and human activity influence carbon sources and sinks both regionally and globally?***

READINESS AND FEASIBILITY

The demand by national and international decision makers for information on the global distribution of carbon sources and sinks and how they are changing will only become stronger as actions to stabilize greenhouse gas emissions and/or manage carbon sequestration are contemplated in the next few decades. It is clear that the best available information, with error estimates and clear characterizations of uncertainties, must be made readily available for use in decision making processes on a regular basis.

There is a wealth of ongoing investment in carbon-related observations worldwide, and systematic observations, from *in situ* networks, inventories, and remote sensing platforms, as well as improved carbon cycling models are now becoming available for use in producing a global synthesis of the best available information. However, these investments have been focused on the needs and observational capabilities of individual programs, agencies, or nations; involve a variety of approaches at various stages of implementation and overall maturity; and, with the exception of certain satellite data sets, do not adequately or evenly sample the globe. This situation is ripe for integration and coordination and presents an opportunity for major scientific breakthroughs. All of the approaches for characterizing carbon sources and sinks (e.g., traditional biometric forest inventories, flask network-derived atmospheric concentrations, ecological models, satellite-derived estimates of primary productivity, eddy covariance flux tower measurements, inverse modeling and boundary layer budgets derived from airborne observations) have known and fairly well understood limitations, and most carry significant errors. Reconciling the estimates from these differing types of observations should enable us to reduce the errors substantially, identify and build confidence in the most appropriate methodologies for continued measurement and monitoring, and, ultimately, balance the global carbon budget (obtaining consistent cross-reservoir estimates and reducing error in all terms) on a year-to-year basis. This integrated approach to analyzing the global carbon cycle, capturing the wealth of available information and deploying a suite of improved carbon cycle models, is what will be needed to produce a comprehensive *State of the Carbon Cycle Report*.

Coordination and integration with monitoring and research programs being conducted by other countries and international scientific organizations is beginning. A partnership has already been forged through the Integrated Global Observing Strategy Partnership (IGOS-P) and is now developing with the Joint Global Carbon Project of the International Geosphere-Biosphere Programme (IGBP), International Human Dimensions Programme (IHDP), and the World Climate Research Program (WCRP) (Hibbard et al., 2001). Plans for global ocean observations (Doney and Hood, 2002) and terrestrial and atmospheric carbon observations (Cihlar, 2001) have been approved through IGOS-P, and one for integrated global carbon observations (land, ocean, and atmosphere) is currently in preparation.

A suite of simple global carbon cycle models, carbon cycle component (e.g., terrestrial ecosystem, ocean) models, and coupled component (land-atmosphere, ocean-atmosphere, ocean biological-physical) models are currently available to support integration and synthesis of global carbon data and information. Most are limited by the availability of data, especially high-quality, long time series data, for initialization or testing. The focus on strengthening observations, monitoring, and data management emphasized by *CCRI* in the U.S. and IGOS-P internationally as well as carbon cycle research to reconcile existing measurement approaches will greatly help in addressing this limitation. Advanced carbon cycle models and new model-data fusion approaches are being developed to further improve global synthesis and analysis. Significant steps are now being taken to develop more fully coupled terrestrial ecosystem-ocean-atmosphere-climate models and carbon data assimilation approaches. Improved integration into carbon models of process understanding is also underway.

Regular reporting on the state of the global carbon cycle should be possible by 2010 – and perhaps sooner if supporting activities are accelerated through the *CCRI*. This *State of the Global Carbon Cycle* report will provide basic information on the most dynamic components of the carbon cycle, for example CO_2 emissions and biological productivity, and updates on what has been learned in the previous period. It will be complemented by less frequent, but more comprehensive reporting on the size, location, and intensity of global carbon sources and sinks, resolved at regional scales and accompanied by an analysis of what is happening and why.

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. Advanced 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. Priority requirements include:

Observations and Monitoring:

- A continued and enhanced global carbon observing system, space-based and *in situ*, in cooperation with international partners – and prioritizing regions identified as under-sampled or as significant sources or sinks for enhancements. Essential components include (see also carbon cycle questions 1, 2, 4, 6): satellite time series data sets of ocean color, vegetation index, LAI, FAPAR, land cover, and winds (for air-sea fluxes), with their *in situ* calibration and validation networks; national vegetation and soil inventories of agricultural, forest, range, and grazing lands; FLUXNET; Long-Term Ecological Research (LTER), ocean mooring time series (i.e., HOTS and BATS), ships-based surveys, and observations from moorings, drifters, and autonomous vehicles.
- New *in situ* observations of soil carbon, above- and below-ground biomass, continuous atmospheric CO_2, and air-sea gas exchange, and measurements to constrain spatial and temporal variability of ocean carbon (see carbon cycle Questions 2, 4, and 6). New measurement concepts and significant technology development investments, as well as national and international partnerships spanning the public and private sectors, will be needed to expand the numbers and/or quality of certain basic carbon observations as well as to provide the first routine measurement of carbon components that have to date been difficult to measure.
- New remote sensing technologies for aircraft and satellites to quantify global carbon sources and sinks (i.e., aboveground biomass and high resolution total column integrals and profiles of atmospheric CO_2) and with resolution, precision, and accuracy sufficient to distinguish and quantify local and/or regional differences (see carbon cycle Question 1, 4, and 6).

Process studies:

- Integrated information on the natural and human system processes controlling global carbon stocks, fluxes, and terrestrial and marine productivity. For example, research is needed on the regional effects of climatic variability and extreme weather events, land management practices, fire, and other forms of disturbance. New and continuing manipulative experiments (see also carbon cycle Questions 1, 4, 5 and 6) are needed to identify the key process controls for global models, and determine which may vary by ecosystem, and to develop understanding of responses to multiple, interacting factors.
- Identify, characterize and quantify the natural and human system processes controlling atmospheric CO_2 and CH_4 growth rates and their interannual variability.

Modeling:

- Further development of ecosystem-carbon cycle models and interactive, coupled atmosphere-ocean-land models with carbon cycling fully incorporated.
- Development of innovative new data assimilation and modeling techniques to guide the integration of separate data streams and incorporate constraints on data and key processes from multiple sources (see also carbon cycle Questions 1 and 2).
- Rigorous testing and evaluation of models, quantifying errors and characterizing uncertainties, and periodic model intercomparison studies (see also carbon cycle Question 1).

Other:

- Assess the needs of stakeholders and decision-making processes to ensure that carbon cycle information provided by the carbon cycle science program is useful.
- International coordination and integration of existing *in situ* observational networks, coordinated planning for network enhancements, and widespread data availability and long-term archival.
- Integrated programs to inter-relate time series of observations from differing sensors in order to ensure the integrity and continuity of the time series. This will be especially important for data products derived from different satellites, sensors, and measurement approaches (e.g., land cover products from optical versus radar remote sensing systems).

PRODUCTS AND PAYOFFS

- U.S. component of international carbon observing system, including observations of carbon storage, carbon fluxes, and complementary environmental data (ongoing; enhancements within 2 years).
- An analysis of the needs of decision makers and other stakeholders, to be achieved by establishing an ongoing dialogue with them, to ensure that carbon cycle information provided in reports on the carbon cycle is useful (< 2 years and to continue).

- Identification and quantification of the processes controlling global CO_2 exchange among the land, ocean, and atmosphere and the processes controlling soil carbon storage from new process and isotope studies (2-4 years).
- An evaluation of the relative roles of processes in the ocean and on the land, and their interactions, in determining the interannual growth rate in atmospheric CO_2 (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 and measurements of carbon stocks associated with that land cover (1 km resolution; 2 years; 30 m; > 4 years).
- Carbon cycle models that use actual global land cover time series characterizations to calculate actual carbon storage: (1 km land cover - 2 years; 30 m land cover - > 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).
- Incorporation of critical potential feedbacks in the regulation of carbon storage and fluxes for the land and ocean into climate models (> 4 years) (in collaboration with the *Climate Variability and Change* element).
- Integrated information on the processes controlling atmospheric CH_4 growth rates and sources and sinks (> 4 years).
- New measurements quantifying global carbon sources and sinks based on new remote sensing technologies (> 4 years).

Policy makers and resource managers will be provided consistent, integrated, and quantitative monitoring data and information on the size, variability, and longevity of 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.

LINKAGES

International cooperation will be absolutely essential to coordinate global observational networks and inter-relate their data, integrate scientific results from around the world, and ensure widespread utility of the State of the Global Carbon Cycle Report and model projections. Continuing partnerships with IGOS-P, the global observing systems (i.e., GTOS, GOOS, GCOS), and the Joint Global Carbon Project of the IGBP, IHDP, and WCRP will be required.

Research on global carbon sources and sinks will require cooperation with all the other *CCSP* research elements as well as other research, operational, infrastructure, and technology development programs. Close coordination with the *Observations, Monitoring, and Data Management* and climate modeling research within the *Climate Variability and Change* and *Applied Climate Modeling* elements will be essential. Linkages to *Human Contributions and Responses* and *Scenario Development* will be important in developing full information for the *State of the Global Carbon Cycle Report*.

High-quality data are being gathered by U.S. and international private sector companies and non-governmental organizations (NGO's) interested in using carbon management projects for offsets; linkages to this work will be needed as well as effective mechanisms for the sharing and integration of data sets and results.

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

Historical and current land use changes and resource management practices impact the overall carbon cycle. Land-cover conversion for human uses has released about as much CO_2 to the atmosphere over the past 150 years as has fossil fuel burning, although the current release is only about 30% that of fossil fuel combustion (Turner et al., 1995). The world's forests are still subject to high rates of clearing and logging, with most present-day releases of carbon to the atmosphere from land conversion occurring as a result of deforestation in the tropics. In the Amazon region alone over 500,000 km^2 of forest has been destroyed during the past 25 years (Houghton et al., 2000). Summed over the entire world, tropical deforestation is estimated to release to the atmosphere approximately 1.6 Pg carbon per year, but there are large uncertainties associated with this estimate (IPCC, 1995).

Not only does land use affect the carbon cycle, but so does its management. For example, land that is converted to agriculture and frequently plowed will continue to be a source of carbon dioxide, because of the oxidation of soil organic matter promoted by extensive tillage. However, reduced tillage and other practices (e.g., cover crops, irrigation, fertility management, buffers, erosion control) can turn agricultural soils into net carbon sinks. In fact, recent estimates indicate that U.S agricultural soils are now a net sink for carbon (Eve, et. al. 2001; Eve et al., 2002). The effects of management practices on other land uses (e.g., urban, water storage reservoirs, landfills, wetlands) are in general poorly understood. Most land uses can be either carbon sources or sinks depending upon how they are managed.

Several recent studies have identified changes in land use and land management as principal driving factors of a North American terrestrial carbon sink. Casperson et al. (2000) identified land cover change, primarily forest regrowth on abandoned agricultural land, as the dominant factor in the United States relative to factors that may enhance growth – CO_2 fertilization, nitrogen deposition, and climate change. For the Northern Hemisphere, Goodale et al. (2002) found that over 80% of the estimated sink occurred in temperate forest regions affected by fire suppression, agricultural abandonment, and plantation forestry. Underlying these observations are long-term shifts in land use. For example, the amount of agricultural land needed in the United States has decreased since the first half of this century. Former agricultural land has been shifting to forest or developed uses for more than a century and the current management of lands remaining in agriculture is promoting soil carbon sequestration.

Carbon sources and sinks in coastal ecosystems are also affected by land use and land management practices. Near-shore marine ecosystems are impacted by runoff of carbon, nutrients, pesticides, and pollutants from adjacent land. Runoff may include nitrogen and phosphorus that can cause eutrophication or transient blooms of phytoplankton, enhancing carbon fixation and export in the coastal zone. By contrast, increases in dissolved organic carbon in coastal environments can enhance bacterial respiration and thus CO_2 production. Terrestrial export of organic carbon to ocean margins seems to be increasing, but the causal factors are still in question (Evans et al., 2002).

The causes and effects of land uses such as timber production, grazing and agriculture, and water storage reservoirs are being studied around the world. For example, the roles of land use, erosion and sediment deposition are being examined in the Mississippi River Basin through measurements of organic carbon accumulation, erosion and burial rates (Stallard, 1998). In the Amazon, the effects of converting primary tropical forest to agriculture or to secondary vegetation is being studied in relation to effects on carbon exchanges among vegetation, soils and the atmosphere (Nobre et al., 1996; Nobre et al., 2001). In the United States, the quantity of carbon retained in durable wood products and sequestered in landfills is significant (Heath et al., 1996). Process models and measurements from these studies are being used to develop a quantitative understanding of the role of land use change and associated erosion and sedimentation processes on carbon storage and nutrient cycles. Methodologies for complete carbon accounting in all land cover types and uses (forests, grazing and range lands, wetland, crop, urban) are being developed.

Conversion of forest usually decreases carbon stocks in biomass and soil, whereas development of agricultural lands may increase or decrease carbon stocks in biomass and soil depending upon previous land use and historical and current land management practices. These changes are not well quantified. Temporal patterns of land cover and use must also be considered. Land management effects are likely to be most important over decadal or century time scales (Barford et al. 2001). Recent work on developing landscape management plans that emulate historical disturbance patterns has stimulated interest in comparing managed landscapes with historical conditions for assessing ecological consequences of alternative land management options (e.g., Harmon and Marks, 2002).

Better cropland management practices (e.g., reduced soil tillage in crop systems, site specific management), increased agricultural productivity, improved forest management, and conversion from cropland to grassland or forest can increase carbon storage in biomass, soil, and wood products. Research, data development and data analysis are beginning to identify those land management practices that can be applied by farmers, ranchers, and forest managers at local scales to reduce carbon emissions or increase carbon storage. Management of land use is a complex issue, with many levels of government, from municipal to federal, also having influence over the process. At larger regional and national scales, information and data derived from inventories, monitoring observations, and experimental studies are used in models to assess ecosystem carbon storage or loss due to land use, land management and land use change. Models also are used to develop land management alternatives, allocation decisions, and policy scenarios.

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?**
- **What are the effects of management practices for near shore ecosystems and land margins on marine carbon storage?**
- **How do processes that control carbon uptake, release, and transport respond to management practices and environmental factors?**
- **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, policy and economic forces influence human decisions regarding land use and resource management, and how might changes in these forcings affect the carbon cycle?**

READINESS AND FEASIBILITY

Comprehensive land, atmosphere, and ocean margin monitoring programs are operational although some significant gaps in data collection have been identified. These existing observational programs provide a strong foundation for research, although enhancements will be needed to answer monitoring needs at various spatial and temporal scales. Better integration of these observational programs is feasible but will require an improved level of interagency coordination.

Government agency and university land management programs have decades of experience in developing and disseminating information about alternative land management practices. Basic and applied research and technology transfer have been well integrated in many instances to serve the needs of land managers. Lacking are studies targeted to the specific objective of carbon management; however, established networks of experimental facilities (forests, watersheds, and farms) provide an excellent foundation for pursuing research directed toward elucidating the effects of management on the carbon cycle. Pilot studies have been conducted that illustrate the feasibility of a much larger program of research.

Carbon cycle models are evolving and improving. With multiple interacting factors to account for, models have become increasingly sophisticated in terms of the processes included, the data required, and the spatial/temporal resolution at which they operate. Yet, few models have the capability to address the very specific needs of land managers who are concerned with local factors and unique sets of land management goals. There is an opportunity to enhance process models for management purposes by linking them with more traditional crop or timber yield models, by validating their application, and by including decision support capabilities that will allow land managers to integrate carbon management with other ownership objectives.

Basic research to further define the mechanisms by which carbon in soil and vegetation is lost to the atmosphere or transferred to stable carbon pools is currently underway. Experimental process studies that control for various influencing factors are beginning (e.g., flux towers in both experimental treatment and control situations). Remote sensing and *in situ* data are being used to improve measurements and mechanistic understanding, increase predictive ability, and evaluate new management strategies to deal with CH_4 and CO_2 generation and uptake. Retrospective studies that take advantage of the Nation's vast network of experimental forests, farms, and watersheds, coupled with ecosystem and hydrologic modeling, are being used to interpret the influence of atmospheric changes and management practices on 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, pastures, rangelands, wetlands, agricultural lands and other ecosystems are needed to provide an essential foundation of ecosystem monitoring data. Many existing sites in the U.S. have rich historical databases. It is important to both maintain the continuity of these key resources and improve capabilities for data synthesis, coordination, and sharing among sites. U.S. carbon cycle research will be conducted in close collaboration with operational resource and inventory programs (e.g., USDA Forest Inventory, Forest Health Monitoring and Natural Resource Inventory, National Cooperative Soil Survey) to ensure the availability of these needed long-term observations of ecological processes, environmental changes and impacts, and treatment effects. Some enhancements to address specific carbon cycle information will be needed. It will also coordinate through activities of the Committee on Earth Observing Satellites (CEOS) and IGOS-P program on Global Observations of Forest Cover and Global Observations of Land Cover Dynamics (GOFC/GOLD) to support consistency and validation of space-based observations across regions and globally.

This work will also depend on an enhanced network of flux measurement sites. Improvements must be made in measurement, monitoring and inventorying methodologies to determine the sizes of the various terrestrial carbon pools (above and below ground). The systematic measurement of soil carbon across soil types, climate regimes, and management systems must be expanded. Soil surveys and soil maps must be digitized and databases must be updated (e.g., National Soils Information System) to include soil carbon information linked to land management information. The stability and permanence of carbon stored under different management practices and under varying climatic regimes needs to be quantified.

Continued research in tropical forest ecosystems is needed to elucidate the effects of deforestation and agricultural land clearing and subsequent cycles of agricultural use, abandonment and recovery, and clearing on carbon storage and emissions to the atmosphere. Research also is needed to quantify the contribution of fires, especially in tropical and boreal ecosystems, to the global carbon balance. Emissions of CO_2 and CH_4 and soot (i.e., black carbon) are of interest. The effects of other land use changes also must be evaluated (e.g., urbanization, extractive harvesting, inputs of sediments, nutrients and pollutants, and wetland creation or drainage).

These studies will require intensive field observations of carbon stocks and fluxes coupled with ecological modeling and remote sensing observations for regional extrapolation. Observations, process studies, and modeling must be integrated to specifically identify the effects of management on the carbon cycle, separated from the many other natural and human effects. This will require a new emphasis on predictive models of observable quantities, quantitative model evaluation, and hypothesis testing. Priority research needs include:

Observations and monitoring:

- Monitor the results of resource management projects that demonstrate carbon sequestration in vegetation and soils (see carbon cycle Question 6).
- Improve *in situ* measurements and estimation methods for carbon in above- and belowground biomass, soils, forest products, woody debris, and litter (see carbon cycle Questions 1, 3, and 6).
- Continued land cover data products from satellites, and estimates of aboveground biomass from newly deployed remote sensing instruments (see carbon cycle Questions 1, 3, and 6).
- Long-term and integrated data products from permanent, experimental and monitoring sites with broad geographic and ecosystem representation.

Process studies:

- Evaluation of the effects of current land management practices (e.g., reduced tillage, residue utilization, forest management, harvest and use) on carbon storage and release, other greenhouse gas emissions, and food and timber production requirements, compared to those of historical practices.

- Long-term manipulative experiments (see also carbon cycle Questions 1, 3, 5 and 6) in conjunction with existing or expanded networks of permanent research, monitoring, and experimental sites.

Modeling:

- Coupled models that link ecosystem, management, policy, and socioeconomic factors (in collaboration with socioeconomic modeling under the *Human Contributions and Responses* element).
- Models to describe spatial patterns of land use and development and their impacts on different carbon pools, at annual to decadal time scales.
- Development of new predictive models that can use inputs on historical land use and management, current production, and land cover, to project observed wood inventories, crop yields, carbon fluxes, and biomass.

PRODUCTS AND PAYOFFS

- Database of agricultural (cropland and grassland) management effects on carbon emissions and sequestration in the U.S., by region, with consideration of effects on all greenhouse gases (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).
- Quantification of the effects of different land use changes and management practices on biomass and soil carbon storage and release, by region, including consideration of multiple goals for resource use (> 4 years).
- Analysis of the effects of historical and contemporary land use and management, and changes in land use and management, on carbon storage and release across environmental gradients (> 4 years).
- Evaluation of the impacts of disturbance (e.g., fire, logging, land conversion) on the fate of carbon in selected ecosystems (2 years) and additional major ecosystems (> 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).

Quantification of past and current effects of land use change and resource management on the carbon cycle will enable policy makers and resource managers to predict how current practices affect the carbon cycle at multiple scales, and to develop alternative policies and practices to mitigate increasing atmospheric carbon (e.g., carbon sequestration through agricultural management practices). Because of the diversity of ecosystems, management practices, and land ownership goals, a regional approach, developed in collaboration with land managers, may be needed to successfully mitigate without producing undesirable side effects. The payoff from this research is potentially large over the next few decades as societies attempt to moderate the increase of greenhouse gases in the atmosphere initially using relatively inexpensive land use and land management options that may also provide additional environmental benefits. Resource management options to mitigate climate change can be an effective strategy while other strategies involving technologies that reduce emissions from fossil fuels are readied for application.

LINKAGES

Research in this area will require close collaboration with the *Land Use and Land Cover Change* research element to document global patterns of land use and land cover, to understand changes in them, and to understand the social drivers of change, as powerful influences on terrestrial carbon sinks and sources. Close collaboration will also be required with the *Ecosystem*s research element to understand natural and human-caused changes in ecosystem structure and function and the processes that affect ecosystem responses to land cover and land use change. Expected products from this research question will feed into the *National Climate Change Technology Initiative (NCCTI)* and provide a strong scientific foundation for deployment of effective carbon management practices.

International cooperation through IGBP, GOFC/GOLD, and other organizations will be necessary to ensure that understanding of these processes is advancing globally and that lessons learned in other countries can be applied, when appropriate, in the U.S. and vice versa. Coordination with the IHDP and various United Nations organizations will be essential, both for integrating understanding of regional variations in land use and management and process controls from case studies around the world and also for ensuring widespread international application of effective carbon 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 potential impacts on natural resources and human populations. We will need to understand the flow of carbon through sources and sinks in the atmosphere, land, and ocean in order to make these projections. Changes in the location, size or intensity of terrestrial or marine carbon sources affect the amount of carbon that is released into the atmosphere, and available to affect the radiation balance of the atmosphere. Similarly, changes in the location, size or intensity of terrestrial or marine carbon sinks directly affect the amount of carbon emissions that remain in the atmosphere, and, thus, must be projected as well (e.g., Falkowski et al., 1998). Because there are numerous sources and sinks of differing character and sensitivity, estimation of their future behavior is difficult. Carbon sources and sinks can be affected by the radiative balance of the Earth (for example, increases in temperature or a longer frost-free period allowing trees to grow and sequester more carbon), and such feedbacks will need to be taken into account. Some sources and sinks are more sensitive to change by (purposeful or inadvertent) human activity than others, thus understanding the degree to which human choices can affect future atmospheric carbon concentrations is further complicated.

Humans, through such mechanisms as the consumption of fossil fuels and the conversion of forests to other uses, have had a profound affect on the carbon cycle. Given projected increases in world population and the desire of lesser-developed countries to improve their standard of living, there is every reason to expect that human activity will continue to have a major influence on the carbon cycle. It is worth noting that to a greater degree than may be true of many factors, the manner in which humans impact the carbon cycle can be self-determined -- i.e., shaped by the policies that humans, through such institutions as government and business, elect to put in place. Before policies that will impact the carbon cycle in desired ways can be established, however, research is needed to expand our knowledge of understanding of how humans and the carbon cycle interact and how human/carbon cycle interactions can be changed.

An important issue of concern in answering carbon cycle Question 5 is reducing the uncertainties in climate change projections by advancing the understanding and modeling of the factors (e.g., ocean, land, and human system behaviors) that determine atmospheric concentrations of carbon-containing greenhouse gases. Estimates of future concentrations of carbon in the atmosphere can be achieved by two complementary approaches. In the first, analogs of future climate states are employed in small-scale manipulative experiments to quantify the behavior of the system in conditions significantly different from those at present (Oechel et al., 1993). In the second, models (both inverse and forward) are constructed and employed to simulate system behavior based on a set of assumed starting conditions and hypothesized system interactions. Four major steps must be taken before useful projections of future carbon concentrations in the atmosphere can be made. First, we need to identify the key interactions and feedbacks. Second, in light of those interactions and feedbacks, we must estimate how the sources and sinks themselves will respond to future climates and the changed CO_2 level. Third, we must develop confidence that the processes are properly represented in models. Fourth we must project the changes in sources and sinks, including estimates of uncertainty. Another issue of concern is related to the consequences of changes in carbon sources and sinks for people; in particular, effects on the productivity of managed ecosystems and the ecological goods and services that human societies depend upon.

The assumption that the carbon cycle will continue to operate just as it has in the recent past is an unlikely future scenario, and underscores the importance of continued research to develop our ability to estimate the response of the carbon cycle to various perturbations. The record of past states of the carbon cycle indicates the system has changed dramatically, and the causes have been attributed to feedbacks (both positive and negative) in the system, non-linear responses, disproportional effects, threshold levels, step functions, self-excitations, and/or dynamical elements (Sarmiento and Wofsy, 1999). There is evidence in the geological and paleoclimatic records that huge, instantaneous releases of CH_4, very likely from clathrate deposits, have disrupted the climate system (Norris and Rohl, 1999; Buffett, 2000). In past periods when the Earth's surface temperature was decreasing, the cooler oceans could absorb more carbon dioxide, resulting in lower atmospheric carbon dioxide concentrations and further cooling (Imbrie et al., 1992). Failure to consider such processes in long-term model projections could result in large over- or underestimates of future atmospheric carbon concentrations, with consequent implications for policy scenarios (Booth et al., 1998).

It has been argued that high latitude regions are the most sensitive areas for detecting global change and have great potential for causing abrupt climate change. Modeling studies indicate that Arctic and boreal ecosystems will be very sensitive to climatic warming. Decreases in permafrost continuity and extent and increases in the active soil layer are anticipated. Since Arctic and boreal peat soils serve as huge reservoirs of carbon, they could emit significant amounts of CO_2 and CH_4 to the atmosphere when warmed (Oechel et al., 1993). However, warmer temperatures and a lengthening growing season could also result in increased photosynthetic carbon uptake (Myneni et al., 1997). The high latitude oceans control thermohaline circulation. Modeled changes in this circulation have shown large changes in carbon dioxide uptake by the ocean.

Our ability to model the carbon cycle has improved dramatically in the past decade. Ocean biogeochemical models are being tested and developed using oceanographic process data, time series measurements, and ocean color observations. Land surface physical models are at an advanced state of development and are being coupled to vegetation and soil models. Longer-term controls over the carbon cycle, such as disturbance and land use are being incorporated as global land cover data improve. Several experiments have been done using coupled carbon-climate models. Data assimilation schemes have been developed for specific processes. For example, ocean carbon data have been used in assimilation schemes to estimate oceanic carbon fluxes and several groups are beginning to assimilate CO_2 flux observations into terrestrial process models. However, much effort is still required to improve models, test their validity, document their uncertainties, and understand their implications. In the next five to ten years, research should advance to allow these models to be used with measurable confidence in projecting the future course of carbon cycling.

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 next few decades and in the next few centuries?***

READINESS AND FEASIBILITY

Global change research investments over the past decade have produced many ecosystem, carbon, biogeochemical cycling, ocean, and atmospheric transport models that will be of use for global carbon cycle modeling and as the basis for developing a next generation of improved models and model projections. There are several different types of carbon models now available, but most lack complete integration of all components, interactive coupling and/or full validation. At present, the best carbon cycling models are limited to only one or two of the major carbon cycle components – typically, either the terrestrial, marine, or atmospheric component; coupled land-atmosphere or coupled ocean-atmosphere; or, alternatively, CO_2 or CH_4. While no single model 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.

In general, available models do not explicitly incorporate the effects of human activities in an interactive system representation; the human impacts are one-way and static. This limits their utility for representing the future state of the carbon cycle and of future climate. The most significant limitation of the current set of scenarios of future human activities is the lack of information on the relative likelihood of the scenarios. If the objective is to reduce the range of uncertainty, finding a technically valid way to assess the plausibility or likelihood of both the individual scenarios and ranges of scenarios is very important. Because most existing tools have well-recognized technical flaws, this is an area in need of creative, new approaches and that requires full collaboration with the *Human Contributions and Responses* element.

The availability of global data sets described under carbon cycle Question 3 and process understanding derived from manipulative experiments and field campaigns described under carbon cycle Questions 1, 2, and 4 also enable the modeling activities under this question.

RESEARCH NEEDS

New and continuing research 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 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. Projections of changes in sinks must be made in ways that are consistent with available data (e.g., carbon inventories and historical data) and our knowledge of natural processes and human behavior. Quantification of errors and communicating an understanding of the significance of uncertainties with these projections will be crucial. Advances in the future will be made through a combination of observations, manipulative experiments and synthesis via models enabled by increases in computational capabilities.

Development of integrative data assimilation and model-data fusion techniques is needed to advance our ability to model the global carbon cycle and to increase the credibility of projections of future carbon cycle functioning. They will need to integrate process models for the land, atmosphere, and oceans; physical, biological, chemical, and fossil carbon observations; and advanced mathematical techniques.

In addition to modeling, field experiments that manipulate environmental variables to determine ecosystem response are important sources of information relevant to future atmospheric CO_2 and CH_4 concentrations and the state of terrestrial and marine carbon sources and sinks. These allow specification of system responses in models and parameterization of such models prior to application. They can also be important in testing and verifying the models once they are applied to a scenario that mimics the field conditions.

Scenarios also need to be improved. The current set of IPCC scenarios includes population forecasts that need updating and combinations of business as usual and policy intervention scenarios in need of refinement. Using improved, integrated and more comprehensive assessment models to develop a revised set of emissions scenarios would be a very helpful step. Collaborations will facilitate the following: 1) improving the modeling of agricultural activities, including long-term growth in productivity and its impact on land use and conversion, and the ability to provide sufficient nutrition to developing countries; 2) improving population forecasts, including the important determinants of fertility, death rates, and migration; 3) revisiting the determinants of long-term demands for food and energy; 4) improving scenarios of future human activity; and 5) evaluating the relative likelihood of the scenarios, including the plausibility and/or likelihood of individual scenarios or a range of scenarios. Priority requirements include:

Process Studies:

- Field experiments that manipulate environmental variables to determine ecosystem responses to changing environmental factors (see also carbon cycle Questions 1, 3, 4 and 6).
- Studies of high latitude terrestrial and marine ecosystems to elucidate the system-level responses to climate variability and change and the key process controls on those responses.
- Research on the drivers of human behavior that affect carbon emissions and storage, and evaluation of the likelihood of fossil fuel emission and land use change scenarios (joint with *Human Contributions and Responses* and *Scenario Development* elements).

Modeling:

- Models to accurately project future carbon storage and release from managed ecosystems that account for natural and human system forcings and responses.

- Improved carbon-climate models that incorporate atmospheric transport; multiple, interactive ecosystem stresses; and human system influences.
- Dynamic, fully coupled Earth system models, incorporating new approaches to treat differences in scale, complexity, and modeling structures to link physical, chemical, biological and human system models (in collaboration with other modeling groups).
- Improved models of atmospheric and ocean transport; multiple, interactive ecosystem stresses; and human system influences in carbon-climate models.
- Detailed testing of predictive models against the observations and integrated understanding of the carbon cycle derived from the research conducted under carbon cycle Questions 1-4 and 6.

Other:

- Advanced computational capability (in cooperation with Climate Modeling).
- New and integrative approaches for conducting social science research to understand how humans affect the carbon cycle (joint with *Human Contributions and Responses* element).

PRODUCTS AND PAYOFFS

- Synthesis of whole ecosystem response to increasing CO_2 based on Free-Air Carbon Enrichment (FACE) experimental manipulation of CO_2 (2-4 years).
- Advanced carbon models that are able to simulate interannual variability at ecosystem and landscape scales and that include the long-term effects of actual land use history (2-4 years).
- Models to predict atmospheric CO_2 concentration at ecosystem and landscape scales and the interannual variability of atmospheric CO_2 (2-4 years).
- Improved understanding 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).
- Estimates of future greenhouse gas concentrations (i.e., CO_2 and CH_4) that can be used to improve projections of future climate changes, as requested by decision makers (2-4 years). Synthesis of whole ecosystem response to combined warming, increasing CO_2, and other environmental changes (> 4 years).
- Advanced carbon models that incorporate improved parameterizations based on results from manipulative experiments and soil carbon transformation studies identifying the fundamental properties and processes controlling carbon sources and sinks (> 4 years).
- Improved projections of climate change forcings (i.e., future 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 uncertainty and errors, from prognostic carbon cycle models.   These models should incorporate an improved understanding of physical, chemical, biological and human processes, including: climate, nutrients, the structure and function of ecosystems, fire, changes in permafrost, other environmental changes, and effects of human activities such as

energy production, use of alternative energy sources, and land and marine resource use (> 4 years).

- Improved, more realistic climate change scenarios, and the relative likelihood of these scenarios, from models projecting future atmospheric greenhouse gas concentrations and carbon-climate interactions and feedbacks (> 4 years). These models must be able to represent forcings and quantify dynamic feedbacks among the carbon cycle, disturbance processes, land cover change, societal activities and the climate system. (joint with *Climate Variability and Change* and *Scenario Development* elements).
- New and integrative approaches for conducting social science research to understand how humans affect the carbon cycle (> 4 years) (joint with *Human Contributions and Responses* element).

New understanding of the controls on carbon cycle process 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.

Studies of the amount of carbon being taken up by North America will provide critical input to discussions of full carbon accounting and carbon credits. However, to develop these decision support products U.S. carbon cycle research will produce critical intermediate products: studies of key processes that will reduce uncertainty, observations of priority components of the carbon-climate system, and improved global climate models (see element on *Climate Variability and Change*). For example, climate models that accurately include the role of aerosols and water vapor in climate forcing and feedback mechanisms as well as realistically project greenhouse gas concentrations should substantially improve our ability to determine the relative importance of reducing aerosol emissions as compared to CO_2 and CH_4 emissions.

LINKAGES

Collaboration with climate modeling research within *CCSP* will be essential for successful projection of future atmospheric CO_2 and CH_4 levels and changes in carbon reservoirs and for incorporating these results into new applied climate model projections. Similarly, modeling of future carbon conditions will require collaboration with the *Human Contributions and Responses* and *Atmospheric Composition* (for CH_4) elements and rely on scenarios requested by decision makers and provided by the *CCRI Scenario Development* element. This will be especially important for addressing fossil fuel emissions and societal choices regarding carbon management. Collaboration with the *Atmospheric Composition* element will focus on developing tools to provide more disaggregated results for relevant emissions and levels of economic activity and to jointly establish estimates of potential changes in sources and sinks for CH_4. Collaboration with the *Climate Variability and Change* element is needed to jointly develop models with interactive climate and carbon cycling, including biotic and human contributions. Joint development with the *Water Cycle*, *Ecosystems,* and *Land Use/Land Cover Change* elements of interactive models linking the water cycle, ecosystems, and land use history models with carbon cycle models also will be required. This modeling is responsive to the Ecological Forecasting initiative proposed in 2000 by the National Science and Technology Council/Committee on Environment and Natural Resources Subcommittee on Ecological Systems. Cooperation with programs that provide national computational infrastructure and data management systems will be essential to support the modeling effort.

The International Geosphere Biosphere Program (IGBP) focuses on relations between changes in earth systems and human impacts on a global scale. Several key programs in IGBP contribute to the global change research program and are integral to understanding the carbon cycle. In particular, IGBP's continuing sponsorship of model intercomparison studies through its Global Analysis, Integration and Modeling (GAIM) core project will be most valuable for future model development and evaluation. Cooperation with the International Human Dimensions Programme (IHDP) will be quite important for modeling that incorporates human contributions and responses.

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 terrestrial and oceanic 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 decision making to manage carbon. Presently, there is limited scientific information to support carbon management strategies, and little is known about the long-term efficacy of practices to enhance carbon sequestration or reduce emissions or how they will affect components of the Earth system (Beran, 1995). This question is not wholly a carbon cycle question, and to address it, research will need to reach beyond the scope of traditional carbon cycle research and significantly involve other Earth science and applications programs and scientists (Hoffert et al., 2002). However, societal interests focused on carbon management engender the need for this research, and carbon cycle science should take responsibility for ensuring the scientific research to answer this question is conducted.

Presently, innovative carbon sequestration research is being conducted in both terrestrial and marine environments. While the potential storage capacity of indigenous ecosystems is vast (Dahlman et al., 2001; Post and Kwon, 2000), a great deal is unknown about how much of this potential can be realized, its permanence, interactions with ecosystem or climate processes, and the possibility of unintended environmental consequences. Enhancing carbon sequestration in soils and forests is a major objective of land use and management studies (Reichle et al., 1999). Such terrestrial sequestration shows tremendous promise, at least in the short-term, for offsetting or producing renewable substitutes for fossil fuel emissions. However, many factors may affect the potential for durable storage in terrestrial sinks, including changing disturbance regimes, changes in permafrost and wetland areas, and changing resource needs and demands. Studies directed toward enhancing terrestrial carbon sinks are investigating forestry practices (e.g., harvest dynamics, pest and pathogen control, utilization and storage of harvested materials, impacts of fire and fire management) and agricultural land management practices (e.g., tillage, crop rotations, and fertilizer use).

The ocean currently serves as a major sink for anthropogenic and natural CO_2 emissions, and ocean carbon sequestration is being considered as a potential carbon management strategy. Two approaches are being investigated for enhancing carbon sequestration in the ocean: 1) direct injection of CO_2 in the deep ocean and 2) iron fertilization to increase the net uptake of CO_2 from the atmosphere by phytoplankton and subsequent export to the deep ocean (Brewer et al., 1999; Coale et al., 1996). Both approaches require further research to determine the effectiveness for long-term carbon storage and their potential environmental consequences.

Current estimates of the optimal sustainable storage capacity that can be realized through terrestrial and oceanic sequestration methods vary, and the uncertainty of those estimates and sources of variability are poorly understood.

RESEARCH QUESTIONS

- ***What are potential magnitudes, mechanisms, and longevity of carbon sequestration by terrestrial and marine systems?***
- ***What is the potential for enhanced ocean carbon sequestration to cause unexpected or undesirable effects on ecosystems, ocean circulation, or climate?***
- ***How do changes in land management, including management of disturbance regimes, such as fire management policies or increased use of biobased products, affect the carbon storage capacity of our forests and rangelands?***
  - What is the longevity of this storage?
  - How compatible are these changes in land management with maintaining and improving productivity and other agricultural values?
- ***How will elevated CO_2, climate variability and other environmental factors (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 potential environmental consequences and sustainability of carbon management approaches?***

READINESS AND FEASIBILITY

The research planned in this area builds on a foundation of many years of global change and natural process research, on research being conducted under the previous five carbon cycle questions, and on national monitoring of forest, rangeland, and agricultural resources. The U.S. federal community and its collaborators in academia and industry are building a strong foundation for the work described here, and the probability of success in characterizing potential impacts of carbon management is high. However, in many instances we are just beginning to develop adequate information on the actual impacts of implementing specific options in specific regions. The challenge is to continually improve our projections of the likely impacts of alternative management scenarios and their feedbacks to the Earth system by integrating knowledge on processes, interactions, and expected responses to human actions and environmental changes. Products and tools in this area, like those developed by West and Marland (2002), must help managers and policy makers make difficult decisions about risks, and must be accompanied by clear statements of their level of reliability.

RESEARCH NEEDS

Research to analyze effects on terrestrial and marine systems and to scientifically assess the short- and long-term efficacy of carbon management practices is needed. Research on the scientific underpinning for carbon management draws on products from carbon cycle Questions 1-5, and will coordinate with the *Ecosystems* element and *NCCTI* as well as public and private programs responsible for developing and/or implementing carbon management. 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. They will need to address the permanence of storage, the potential for displacement of emission-producing activities to other regions, and the ability to verify actual carbon storage.

Experiments will be conducted to understand plant and ecosystem responses to terrestrial carbon sequestration, and to evaluate effects of enhanced nutrient availability and elevated CO_2 on carbon uptake. 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, decision-making processes that involve multiple land management scenarios, and the role of sequestration mechanisms for calculating net carbon emissions intensity (gross emissions minus carbon storage). Experiments and process studies also will be needed to evaluate the likelihood of unintended environmental consequences of enhanced carbon sequestration practices.

Research on the effects of direct injection of CO_2 into the ocean is needed at a range of scales. It is needed both to improve our knowledge of the fate of the injected CO_2 and to quantify its effects on deep-sea ecosystems and the marine environment. Fundamental questions remain on the effect of iron fertilization on carbon export to the deep ocean, and additional research is needed. Priority requirements for terrestrial and ocean carbon sequestration include:

Observations and monitoring:

- Monitor environmental conditions and ecosystem responses at sites demonstrating carbon management technology.
- Augmented inventories for ecosystem carbon and refined estimation methods for forest products in use and disposed of in landfills (see carbon cycle Questions 1, 3 and 4).

Process studies:

- Continued research to identify decision-making processes with respect to carbon management in the context of several land management scenarios.
- Experiments to evaluate plant and ecosystem response, including manipulative experiments to understand the effects of enhanced nutrient availability and elevated CO_2 on carbon uptake and retention in managed ecosystems (see also carbon cycle Questions 1, 3, 4 and 5).
- In the context of direct injection, determine the effects of changes in pH and elevated CO_2 concentrations on the physiology and ecology of mid-water and deep-sea organisms.
- Increased understanding of the physical, chemical, and biological behavior of injected CO_2 hydrate plumes using laboratory studies, small-scale ocean injections, and near-field plume dynamics modeling.
- Field experiments to monitor the ecological impacts and characterize far field effects of CO_2 injection in the ocean.
- Increased understanding of the "biological pump" (the natural process of carbon fixation by phytoplankton followed by the gravitational settling of particulate carbon to the deep sea) and the nutrients (including iron, nitrogen, silicon and phosphorus) that regulate it (also relevant to Carbon Cycle Question 2).
- Determination of the impact of enhanced carbon sequestration on biogeochemical cycling of key elements in the ocean including carbon, nitrogen, silicon, phosphorus and trace metals.
- Evaluation of the effects of iron fertilization in the ocean on the composition of phytoplankton and zooplankton communities and on the oceanic food web and trophic dynamics (see carbon cycle Question 2).

Modeling:

- Models to assess the economics of carbon management options in the agricultural and forestry sectors, including full life cycle analysis of carbon.
- Models that incorporate understanding of basic processes (e.g. photosynthesis, genetics, ecosystem-specific rates of carbon storage and loss through biochemical and physical processes) into evaluation of natural and enhanced mechanisms of carbon sequestration.

- Models that link effects of climate on the health and productivity of forests, rangelands, and agricultural lands to their potential to supply wood, fiber, bioenergy, food, and other products.
- Integration of the results of the laboratory, field and modeling studies of CO_2 injection into the ocean into specific injection scenarios that optimize cost and effectiveness, while minimizing adverse environmental impacts.
- Improved parameterization of biological processes in models of iron fertilization, and validation of models of sustained fertilization, using data from field experiments.

PRODUCTS AND PAYOFFS

- First assessment of the effects of small-scale direct injection of liquid CO_2 into the deep ocean on the chemistry and marine biology of deep-sea sediments (2 years).
- New monitoring techniques and strategies to improve quantitative measurement of the efficacy of carbon management activities (2-4 years).
- Evaluation of the biophysical potential of U.S. ecosystems to sequester carbon (selected regions: 2 years; U.S.: 4 years) and assessment of management practices for carbon sequestration in crops and grazing systems (warm and cool season grasses: 2 years; crops, irrigated crops, and grazing systems > 4 years).
- Improved global and regional models to quantify long term effectiveness of direct injection of CO_2 into the deep ocean (2-4 years) and to identify potential sites for injection (> 4 years).
- Improved global and regional models to quantify the effectiveness of iron fertilization (2-4 years) as well as potential for unintended effects on biogeochemical cycles and marine trophic dynamics (>4 years).
- Improved accounting methods for carbon taking into account the impacts of wildfire and fuel management practices, forest management practices, utilization techniques, and other factors controlling carbon sequestration and the release of carbon and other greenhouse gases from forests and forest products (4 years).
- Scientific criteria and model tests of the sustainability of carbon management that take into account disturbance processes, system interactions, and feedbacks (> 4 years).
- Analysis of options for science-based carbon management decisions and deployment by landowners (> 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).
- Management practices to minimize greenhouse gas intensity (gross emissions minus carbon storage) of agricultural cropping and grazing systems (> 4 years).
- Improved accounting of CH_4 emissions from animal feeding operations and options for reducing these CH_4 emissions (> 4 years).
- Models that treat photosynthesis, molecular biology of carbon partitioning, rates of carbon turnover, and longevity of carbon storage (> 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 intensity, and for full carbon accounting.

LINKAGES

This research to provide a scientific underpinning for carbon management links closely to the *National Climate Change Technology Initiative (NCCTI)*, which focuses on engineered technologies, carbon offsets, and economic systems. It will be conducted in collaboration with the *Ecosystems* element, the *Land Use/Land Cover Change* element, and public and private programs responsible for monitoring, or developing and implementing carbon management for sequestration or emissions reduction (e.g., USDA/DOE Biobased Products and Bioenergy Initiative, USDA Consortium for Agricultural Soils Mitigation of Greenhouse Gases (CASMGs), USDA Greenhouse gas Reduction through Agricultural Carbon Enhancement Network (GRACEnet), DOE Carbon Sequestration in Terrestrial Ecosystems (CSiTE), USDA Inventory and Monitoring Programs (Forest Inventory and Analysis, Forest Health Monitoring, and Natural Resource Inventory Programs; experimental forests and ranges, National Fire Plan), the NSF Long Term Ecological Research (LTER) Program and National Environmental Observation Network (NEON) initiative, and process-based research and modeling programs in all *CCSP* agencies). Research on ocean carbon sequestration will continue to be coordinated with the fourteen agencies represented in the National Ocean Partnership Program (NOPP) and with Ocean.US, which is coordinating ocean observation data for the U.S. component of GOOS.

Improved linkages will need to be developed between the ecological and social science research communities, and with the managers and policy-makers who will use the information that is produced. These connections are necessary to ensure that products developed are not only scientifically sound, but also incorporate the relevant social and economic considerations. Emphasis will be placed on products that are useful to the user community in planning and decision-making.

Conclusion

National and international decision makers 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 management options for climate change mitigation. U.S. carbon cycle research, in cooperation with other U.S. and international programs, will bring together the needed infrastructure, resources, and expertise to provide important scientific information to meet these needs. The carbon cycle will be studied as an integrated Earth system carbon cycle in order to identify, understand and quantify the processes controlling carbon, to understand how source and sink regions change over space and time, to improve capabilities to anticipate future climatic conditions, and to help make informed management decisions. A near-term priority is to identify, characterize, quantify, and predict North American and adjacent ocean carbon sources and sinks.

U.S. carbon cycle science will be conducted in close cooperation with all the other *CCSP* research elements as well as other research, operational, infrastructure, and technology development programs, in both the public and private sectors. Cooperation with programs that provide national computational infrastructure, data management systems, and ongoing monitoring will be essential. Full collaboration with the *Land Use/Land Cover Change* research element on 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. 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. Collaboration with the *Ecosystems* element will be required throughout, especially in securing needed observations and in ecosystem model development. The *Carbon Cycle* element will rely on the *Ecosystems* element for many needed process studies and collaboration on large-scale, multi-factor manipulative experiments. Close cooperation with the *Atmospheric Composition* element will be essential for the NACP and in research on CH_4. Interactions with the *Water Cycle*, *Applied Climate Modeling*, *Human Contributions and Responses*, *Climate Variability and Change*, and *Scenario Development* research elements also will be important – especially for integrated Earth system modeling.

International cooperation will be necessary to coordinate global observational networks and inter-relate measurements, integrate scientific results from around the world, and ensure widespread utility of the *State of the Carbon Cycle Reports* and model projections. Close cooperation with Canada and Mexico under the NACP will be essential to its success. Partnerships are anticipated with IGOS-P and the global observing system programs (GTOS, GOOS, and GCOS). Interactions with and contributions to the joint Global Carbon Project of IGBP, IHDP, and WCRP will be important. U.S. carbon cycle research will contribute to bilateral activities being developed by the administration.

Information gained from research conducted under all six carbon cycle questions will be essential to success in providing useful information for decision makers at many levels in society, from land and resource managers to national and international policy makers. An integrated approach, accounting for carbon as it cycles among the ocean, land and atmosphere and as it is directly affected by human activities, will be essential to providing accurate assessments of carbon balance, improved projections of future atmospheric concentrations of CO_2 and CH_4, and the scientific understanding necessary to evaluate options. This integration will need to be accomplished through joint planning and coordinated implementation across the various U.S. Government agencies involved. A continuing dialogue with stakeholders will need to be established and maintained to ensure that desired information is provided in a useful form. The scientific community will be looked to for continuing leadership in identifying the important research questions and scientific approaches, in carrying out the program of research, and in assessing its results.

Scientific information and data resulting from U.S. carbon cycle research will be regularly assessed and integrated into products and information that can be used for decision support. Improved models, well-characterized data sets, and scientific information will be made available for national and international assessments. Regular reports on the state of the carbon cycle, first for North America and later for the global carbon cycle, will be produced.

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