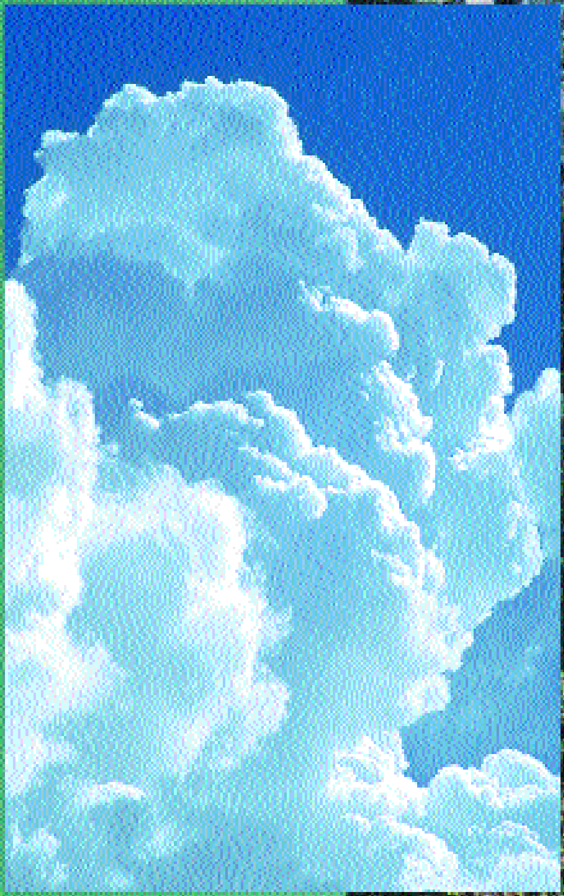
A U.S. CARBON CYCLE SCIENCE PLAN



A Report of the
Carbon and Climate Working Group
Jorge L. Sarmiento and Steven C. Wofsy, Co-Chairs

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Prepared at the Request of the Agencies of the
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The Working Group began its work in early 1998, holding meetings in March and May 1998. A Carbon Cycle Science Workshop was held in August 1998, in Westminster, Colorado, to solicit input from the scientific community, and from interested Federal agencies. The revised draft Plan was made available for input by a broad segment of the scientific community.

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Executive Summary

Rationale

Carbon on earth is stored primarily in rocks and sediments. Only a tiny fraction resides in mobile reservoirs (the atmosphere,oceans,and soil and terrestrial biosphere) and is thus available to play a role in biological, physical and chemical processes at the earth's surface. The small fraction of carbon present in the atmosphere as carbon dioxide (CO_2) is especially important: it is essential for photosynthesis,and its abundance is a major regulator of the climate of the planet.

The major gases,nitrogen, oxygen,argon,which comprise over 98% of the atmosphere,are transparent to far-infrared (heat) radiation. Trace gases such as carbon dioxide, water vapor, nitrous oxide,and methane absorb heat radiation from the surface, warming the atmosphere and radiating heat back to the surface. This process,called the *greenhouse effect*, is a natural phenomenon without which the Earth's surface would be 30°C cooler than it is at present.

Throughout the climate extremes of the past 400,000 years,during which there were four major glacial cycles, atmospheric CO_2 concentrations varied by no more than twenty percent from a mean of about 240 parts per million (ppm). Concentrations of CO_2 and methane are now higher by more than 30% and 250%, respectively, than the previous maxima. This very rapid increase has occurred since the industrial revolution, raising concerns that the temperature of the atmosphere may rise as a consequence of an increase in the greenhouse effect.

The rapid increase in atmospheric concentrations of CO_2 over the past 150 years, reaching current concentrations of about 370 ppm, corresponds with combustion of fossil fuels since the beginning of the industrial age. Conversion of forested land to agricultural use has also redistributed carbon from plants and soils to the atmosphere. There has been growing concern in recent years that these high levels of carbon dioxide not only may lead to changes in the earth's climate system but may also alter ecological balances through physiological effects on vegetation.

Only about half of the CO_2 released into the atmosphere by human activity ("anthropogenic"CO_2 from combustion of fossil and biomass fuels and from land use changes) currently resides in the atmosphere. Over the last 10-20 years,more than half of the CO_2 released by burning fossil fuels has been absorbed on land and in the oceans. These uptake and storage processes are called "sinks" for CO_2, although the period over which the carbon will be sequestered is unclear. The efficiency of global sinks has been observed to change from year to year and decade to decade,due to a variety of mechanisms,only partly understood.

The understanding of carbon sources and sinks has advanced enormously in the last decade. There is now clear evidence that global uptake of anthropogenic CO_2 occurs by both land plants and by the ocean. The magnitude of the oceanic sink, previously inferred from models and observations of chemical tracers such as oceanic radiocarbon and tritium distributions, has recently been confirmed by direct observation of the increase in dissolved inorganic carbon. Analysis of new tracers such as chlorofluorocarbons provide further refinements to our understanding of carbon uptake by the oceans. The importance of the sink due to the terrestrial biosphere has emerged from analysis of the global carbon budget,including improved estimates of the ocean carbon uptake, as well as data on $^{13}CO_2/^{12}CO_2$ isotopic ratios and from changes in the abundance of O_2 relative to N_2. Isotopes can give information on the terrestrial sink, for example, since plants preferentially select certain isotopes during photosynthesis and leave a global signature in the isotopic ratio of carbon dioxide in the atmosphere. Forest inventories and remote sensing of vegetation appear to confirm a significant land sink in the Northern Hemisphere and provide insight into the underlying mechanisms. However, we cannot yet quantitatively define the global effects of human activities such as agriculture and forestry or the influence of climate variations such as El Niño. Studies to determine these effects have emerged as critical for understanding long-term changes in atmospheric concentration in the past, and will help to dramatically enhance understanding of how the earth's climate will evolve in the future.

The Carbon Cycle Science Plan (CCSP) presented in this document has several fundamental motivations. First, it is clear that the oceans and land ecosystems have responded in measurable ways to the atmospheric increase in carbon dioxide,but the associated mechanisms are still not well quantified. Second,the land and ocean sinks and sources appear to fluctuate naturally a great deal over time and space,and will likely continue to vary in ways that are still unknown. Third,to predict the behavior of Earth's climate system in the future, we must be able to understand the functioning of the carbon system and predict the evolution of atmospheric CO_2. Finally, scientific progress over the past decade has enabled a new level of integrated understanding that is directly relevant to critical societal questions associated with the economic and environmental effects of forestry, agriculture,land use and energy use practices.

The development of the CCSP has been strongly influenced by the view that carbon cycle science requires an unprecedented coordination among scientists and supporting government agencies. The nature of the problem demands it. Carbon dioxide is exchanged among three major active reservoirs,the ocean,land,and atmosphere, and through a variety of physical, chemical,and biological mechanisms,including both living and inanimate components. Research on atmospheric CO_2 therefore encompasses the full Earth system and involves many different research disciplines and approaches.

Consequently, a large number of government agencies and programs are involved in supporting research on the carbon cycle,including data-gathering, field research, analysis,and modeling. Thus it is clear that there is extraordinary value to be gained by coordinating research and encouraging disciplinary and organizational cross-fertilization through effective program integration. In addition,a recent report evaluating research programs in global environmental change by the National Research Council highlighted the importance of developing a coordinated, focused,scientific strategy for conducting carbon cycle research (NRC 1998[1]).

The Carbon Cycle Science Plan presents a strategy for a program to deliver credible predictions of future atmospheric carbon dioxide levels, given realistic emission and climate scenarios, by means of approaches that can incorporate relevant interactions and feedbacks of the carbon cycle-climate system. The program will yield better understanding of past changes in CO_2 and will strengthen the scientific foundation for management decisions in numerous areas of great public interest.

The intent of the CCSP is to develop a strategic and optimal mix of essential components, which include sustained observations,modeling, and innovative process studies,coordinated to make the whole greater than the sum of its parts.The design of the CCSP calls for coordinated, rigorous,interdisciplinary scientific research that is strategically prioritized to address societal needs. The planned activities must not only enhance understanding of the carbon cycle, but also improve capabilities to anticipate future conditions and to make informed management decisions.

Basic Strategy

There are two components to the CCSP strategy:

- Developing a small number of potent new research initiatives that are feasible,cost-effective,and compelling, to improve understanding of carbon dynamics in each carbon reservoir and of carbon interactions among the reservoirs.
- Strengthening the broad research agendas of the agencies through better coordination, focus,conceptual and strategic framework,and articulation of goals.

Scientific Questions

In the very broadest terms,the present plan addresses two fundamental scientific questions:

- What has happened to the carbon dioxide that has already been emitted by human activities (past anthropogenic CO_2)?
- What will be the future atmospheric CO_2 concentration trajectory resulting from both past and future emissions?

The first of these questions deals with the past and present behavior of the carbon cycle. Information about this behavior provides the most powerful clues for understanding the disposition of carbon released as a result of human activities,the underlying processes in this disposition,and their sensitivity to perturbations. Improved understanding will require targeted historical studies,the development of a sustained and coordinated observational effort of the atmosphere,land and sea,and associated analysis,synthesis,and modeling.

The second question focuses directly on the goal of predicting future concentrations of atmospheric CO_2. The study of essential processes in the carbon cycle will be integrated with a rigorous and comprehensive effort to build and test models of carbon cycle change,to evaluate and communicate uncertainties in alternative model simulations,and to make these simulations available for public scrutiny and application. The research program outlined in the CCSP will depend on parallel initiatives in human dimensions programs to fully achieve its goals,especially that of predicting future atmospheric CO_2 concentrations.

Current estimates of terrestrial sequestration and oceanic uptake of CO_2 vary significantly depending on the data and analytical approach used (e.g.,the Forest Inventory Analysis,direct flux measurements in major ecosystems,inverse model analysis of CO_2 data from surface stations, changes over time of global CO_2, O_2, $^{13}CO_2/^{12}CO_2$, measurement based estimates of the air-sea CO_2 flux and dissolved inorganic carbon inventory, and ocean and terrestrial vegetation model simulations). The proposed program is designed to reconcile these estimates to a precision adequate for policy decisions by delivering new types of data;applying new, stringent tests for models and assessments;and providing quantitative understanding of the factors that control sequestration of CO_2 in the ocean and on land. A sound basis for policy debates and decisions will be provided by the program as fully implemented.

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[1] National Research Council,Global Environmental Change:Research pathways for the next decade,National Academy Press,Washington, D.C.,1998.

Long-Term Goals

The elements of the proposed program (see the sections that follow) have the following long term objectives:

Scientific Knowledge and Understanding

- Develop an observational infrastructure capable of accurately measuring net emissions (sources and sinks) of CO_2 from major regions of the world.
- Document the partitioning of carbon dioxide sources and sinks among oceanic and terrestrial regions.
- Understand the processes that control the temporal trends and spatial distribution of past and current CO_2 sources and sinks, and how these might change under future conditions of climate and atmospheric chemistry.
- Determine quantitatively the factors (long term and transient) that regulate net sequestration of anthropogenic CO_2.
- Develop the ability to predict and interpret changes in atmospheric CO_2 in response to climate change and inputs of CO_2, and including changes in the functional aspects of the carbon cycle.

Application of Scientific Knowledge to Societal Needs

- Develop atmosphere-ocean-land models of the carbon cycle to (1) predict the lifetimes, sustainability, and interannual/decadal variability of terrestrial and ocean sinks, and (2) provide a scientific basis for evaluating potential management strategies to enhance carbon sequestration.
- Develop the ability to monitor the efficacy and stability of purposeful carbon sequestration activities.
- Develop the capability for early detection of major shifts in carbon cycle function that may lead to rapid release of CO_2 or other unanticipated phenomena.

Program Goals for Fiscal Years 2000-2005 and Associated Program Elements

Achieving these goals requires new mechanisms to integrate information on the carbon cycle and coordinate interagency efforts as well as additional funding in critical areas as described below. The following goals will provide high-value deliverables upon full implementation of the proposed program.

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

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

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

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

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

The potential for near-term progress is demonstrated by the identification of two general hypotheses that are testable by integration of the program elements described below.

Hypotheses:

1. There is a large terrestrial sink for anthropogenic CO_2 in the Northern Hemisphere.
2. The oceanic inventory of anthropogenic CO_2 will continue to increase in response to rising atmospheric CO_2 concentrations, but the rate of increase will be modulated by changes in ocean circulation, biology, and chemistry.

Goal 1: Understanding the Northern Hemisphere Land Sink

Goal 1 is intended to establish accurate estimates of the magnitude of the hypothesized Northern Hemisphere terrestrial carbon sink and the underlying mechanisms that regulate it.

Major Program Elements and Activities

- Expand atmospheric monitoring: vertical concentration data, column CO_2 inventories, continuous measurements, new tracers (oxygen, carbon and oxygen isotopes, radon, CO, and other traces gases).
- Conduct field campaigns over North America, and eventually over the adjacent oceans, using aircraft linked to enhanced flux tower networks and improved atmospheric transport models.
- Improve inverse models and strengthen connections between atmospheric model inferences and direct terrestrial and oceanic observations.

- **Expand the network of long-term flux measurements for representative ensembles of undisturbed,managed, and disturbed land along major gradients of soils,land use history, and climate,using new technology to lower costs.**
- **Conduct manipulative experiments and process studies on ecosystem,local,and regional scales,coordinated with flux measurements to quantify terrestrial sources/sinks and changes over time.**
- **Obtain remote-sensing data defining changes in vegetation cover and phenology.**

Deliverables

- **Define the existence and magnitude of past and present terrestrial carbon sinks.**
- **Elucidate the contributions of climate variations,such as rainfall,length of growing season,soil moisture,and long-term temperature changes,of fertilization (CO_2, NO_x, etc.),and of past and present land use changes and land use management to the contemporary CO_2 sink.**
- **Document and constrain the uncertainties related to the potential Northern Hemisphere terrestrial carbon sink.**

Goal 2: Understanding the Ocean Carbon Sink

Goal 2 is intended to establish accurate estimates of the oceanic carbon sink,including interannual variability, spatial distribution,sensitivity to changes in climate,and underlying mechanisms. In the near-term, focus should be given to the North Atlantic and North Pacific to complement the focus on the Northern Hemisphere in Goal 1. In the long term, focus should be on important regions with major gaps in current knowledge,such as the Southern Ocean.

Major Program Elements and Activities

- **Develop new technology for measuring oceanic CO_2 and related quantities on various observational platforms,including moorings,drifters,and new shipboard sampling techniques.**
- **Acquire air-sea carbon flux measurements,including data from long-term stations and from field campaigns combining aircraft,shipboard,and shore-based measurements;use improved ocean and atmosphere transport models to refine estimates of the magnitude of oceanic sources and sinks of CO_2 based on pCO_2 (partial pressure of carbon dioxide) data.**
- **Synthesize results of recent global ocean carbon surveys to elucidate the processes for carbon storage in the sea,and conduct ongoing oceanic inventory and tracer measurements at a level that assures coverage of all ocean areas every 10 to 15 years.**
- **Develop and implement process studies,models,and synthesis,including manipulation experiments,large-scale tracer releases,and direct measurement of air-sea fluxes of CO_2;focus should be on defining physical and biological factors regulating air-sea exchanges and export to long-term storage in deep ocean waters.**
- **Develop remote sensing capability to monitor physical and biological properties on larger scales.**

Deliverables

- **Understand ocean processes in critical regions such as the Southern Ocean.**
- **Determine the existence,magnitude,and interannual variability of oceanic carbon sinks and sources on regional scales.**
- **Attribute observed changes in the ocean carbon sink to variations in circulation,biology, and chemistry.**
- **Incorporate improved oceanic CO_2 flux estimates for better constraints on inverse models in estimating terrestrial sinks.**

Goal 3: Assessing the Role of Land Use

More fully stated,Goal 3 is to obtain accurate esti--mates of the effects of historic and current land use patterns on atmospheric CO_2, emphasizing the tropics and Northern Hemisphere.

Major Program Elements and Activities

- **Document the history of agricultural expansion and abandonment and its impact on the contemporary carbon balance of North America by conducting intensive historical land use and present-day land management analyses across environmental gradients in coordination with the proposed North American network of eddy flux measurement sites.**
- **Improve observational capabilities in tropical regions through cooperation with tropical nations,including international expeditions and exchanges and training of scientists and managers.**
- **Apply the observational programs discussed in Goal 1 in the tropics,including long-term observations and modeling.**

- Couple historical and socioeconomic analysis of land management strategies with biogeochemical models to evaluate the integrated effects of human activities that sequester carbon (see Goal 5).

Deliverables

- Document the existence,location,and magnitude of carbon sources and sinks resulting from historical and current land use change and land management.
- Provide the scientific basis for evaluating short-term and long-term impacts of deliberate modification of the terrestrial biosphere
- Provide better assessments of carbon balance uncertainties related to land use,particularly agriculture in North America and the tropics.

Goal 4: Improving Projections of Future Atmospheric CO_2

More fully stated,Goal 4 is to improve projections of future atmospheric concentrations of CO_2 through a combination of manipulative experiments and model development that incorporates appropriate biophysical and ecological mechanisms and carbon cycle-climate feedback into global climate and carbon cycle models.

Major Program Elements and Activities

- Improve representation of physical and biological processes in carbon and climate models.
- Provide a framework for rigorous analysis of observations and for independent comparisons and evaluations of climate and carbon models using comprehensive data and model assessment activities.
- Develop new generations of terrestrial biosphere and ocean carbon exchange models that include the roles of both natural and anthropogenic disturbances,succession,and the feedback through changes in climate and atmospheric composition.
- Develop coupled Earth system models incorporating terrestrial and oceanic biogeochemical processes in climate models.
- Provide projections of the future evolution of CO_2 concentrations to evaluate the consequences of different emission scenarios and to provide a scientific basis for societal decisions.

(See under Goal 5, for deliverables.)

Goal 5: Evaluating Management Strategies

Goal 5 is to develop a scientific basis for evaluating potential management strategies to enhance carbon sequestration in the environment and capture/ disposal strategies.

Major program elements and activities

- Synthesize the results of global terrestrial carbon surveys, flux measurements,and related information; strengthen the scientific basis for management strategies to enhance carbon sequestration.
- Determine the feasibility, environmental impacts,stability, and effective time scale for capture and disposal of industrial CO_2 in the ocean and geological reservoirs.
- Define potential strategies for maximizing carbon storage that simultaneously enhance economic and resource values in forests,soils, agriculture,and water resources.
- Identify criteria to evaluate the vulnerability and stability of sequestration sites to climate change and other perturbations.
- Document the potential sustainability of different sequestration strategies and the storage time for sequestered CO_2.
- Develop the monitoring techniques and strategy to verify the efficacy and sustainability of carbon sequestration programs.
- Develop scientific uncertainty estimates that are required for policy discussions and decisions related to managed carbon sequestration.
- Create a consistent database of environmental,economic,and other performance measures for the production, exploitation,and fate of wood and soil carbon “from cradle to grave”(for wood,from stand establishment through final disposal; for soil carbon,from formation through burial).

Deliverables (Goals 4 and 5)

- Present a new generation of models, rigorously tested using time-dependent 3-dimensional data sets,suitable for predicting future changes in atmospheric CO_2.
- Support the development of management/mitigation strategies that optimize carbon sequestration opportunities using terrestrial ecosystems,primarily forest and agricultural systems,as well as evaluating the efficiency of sequestration in the ocean
- Use these new models to identify critical gaps in our understanding and help design future observational strategies.

Program Elements and Resource Requirements*

The table below breaks out the program elements and summarizes the corresponding research components and approximate costs. In the following section of the Executive Summary, these elements are mapped onto the program goals that were outlined above. Both program goals and program elements are discussed in greater detail in Chapter 4 and Chapter 6.

Project Element	Deliverable	Description	Development/Start-up	Operations Cost
1. Expanded Flux Network[†]	Net CO_2 exchange across major biophysical gradients	100-150 eddy flux network sites, operated long-term	Technology dev-. ($5M) and initial installation, ($15M) over 5 yrs	$20M/yr
2. Airborne CO_2 Observation Program[†]	Three-dimensional and temporal distributions of CO_2 and tracers over North America, analyzed to define regional sources/sinks, and constrain atmospheric transport models	Newly developed weekly monitoring network at 50 distributed North American sites deployed on general aviation aircraft with a combination of flask and on-board continuous sampling units; development and operation supported by periodic intensive field measurements (element 6 below)	$10M	$10M/yr
3. Global CO_2 Monitoring Network	Enhanced space/time data for CO_2 and tracers, defining regional sources/sinks on a global scale, and constraining atmospheric transport models	Increased number (by a factor of 3) of flask and continuous monitoring stations measuring CO_2 and tracers, emphasizing continental and remote marine locations; vertical profiles at selected locations as specified in element 2.		$10M/yr
4. Global Terrestrial Carbon and Land Use Inventories	Vegetation cover, above-and below-ground carbon, and rates of change; input data, constraints, and representation of mechanisms in biogeochemical models	(a) Expanded and reformed Forest Inventory Analysis program to include carbon as a focus, with shorter return intervals, more ecological measurements and greater transparency and traceability (b) New satellite observations (nested high-resolution and LANDSAT imagery, new radar mapping) (c) Analysis of current soil carbon inventories and expansion to monitor eroded carbon and other effects of land use on soil carbon	(b) $10-30M/yr for 5 yr (c) $5M	(a) $10M/yr (b) $10M/yr (c) $5M/yr
5. Reconstruction of Historical CO_2 Emissions	Estimates of historical sources and sinks due to human land use, to be used to constrain predictive models.	Analysis of existing data, synthesis into data sets available for carbon modeling, and development of new historical carbon-cycle models; significant role for remote sensing (LANDSAT 7, MODIS)	$2M	$2M/yr
6. Regional Observational Experiments	Direct regional determinations of fluxes and concentrations of CO_2, greenhouse gases, pollutants	Coordinated airborne, ship, terrestrial, and satellite experiments integrated with model development and testing (e.g. BOREAS)		$5-10M/yr
7. Long-Term Terrestrial Observations	Long-term vegetation, soil, and flux data for major biomes, new emphasis on disturbed and managed sites	30-40 long-term regional sites to evaluate natural disturbance and management effects on carbon fluxes (e.g. increasing focus on carbon, and greater number and types of sites in the NSF LTER network)		$40M/yr
8. Terrestrial Process Studies and Manipulations	Long-term, large-scale effects on the biosphere and on carbon sequestration of predicted environmental changes not occurring in nature today	20-30 major, long-term experiments at ecosystem scale manipulating CO_2, nutrients, water, ozone, temperature, etc.	$20-30M	$20-30M/yr
9. Global Ocean Measurements (surveys, time series, remote sensing)	Ocean/atmosphere fluxes; basin-scale net uptake of anthropogenic CO_2 at reduced cost, and interpretation of seasonal variances, atmosphere-ocean-biology interactions.	(a) Complete analysis of recent global survey data (b) Develop and deploy time-series and drifting buoys and automated towed vertical samplers for CO_2 and related parameters (DIC, DOM,POM, alkalinity, O_2, nutrients, $^{13}CO_2$, $^{14}CO_2$, T, S) and tracers of ocean circulation (CFCs, ^{14}C, $^3H/^3He$), reduce cost per measurement, increase data flow	$25M	$30-50M/yr
10. Ocean Process Studies and Manipulations	Define effects of biology, circulation, atmospheric deposition, and river fluxes on the distribution of oceanic carbon, and rates of invasion/release of industrial CO_2	(a) Physical and biological studies of dispersion of anthropogenic CO_2 and controls on new production/uptake (b) Ocean manipulation experiments (~2/yr duration) to examine hypotheses such as the role of iron in ecosystem production		(a) $10M/yr (b) $10M/yr
11. Modeling and Synthesis	Develop and apply models for analysis of data, synthesis, prediction, policy	Improved ocean, atmosphere and land simulations, rigorous, independent, comparisons of models with data. Develop Earth System models that predict CO_2 and climate interactively		$15-30M/yr
TOTALS	**Present new knowledge, meet societal needs, devise cost-effective approaches**	(Note: estimated current annual spending for carbon-focused work in FY1998 was $40-50M)	$135-300M over 5 years	$200-250M/yr

*For explanation of acronyms, see the acronym list at the end of this report.

[†] Technology development will be a critical focus in the initial phase of this activity.

Mapping of Program Elements to CCSP Goals

The following paragraphs map the program elements shown in the table above to the goals and objectives of the Carbon Cycle Science Plan.

Goal 1: Program Elements 1-4, 6-9, 11

The program elements (1) expanded terrestrial flux network, (2) airborne CO_2 observation program, (3) global CO_2 monitoring network, and (4) land use inventories, taken together, address the first part of the CCSP Goal 1: to quantify the Northern Hemisphere terrestrial sink and more generally, to quantify the global terrestrial sink for CO_2. Program elements (1), (2), and (3) together provide direct long-term measurements defining sources and sinks on regional scales. The proposed airborne observations (2) are capable of providing integrated measures of regional net exchange several times per month; the conceptual framework for interpreting these observations needs to be strengthened and tested through a series of strategically planned regional observation experiments (6).The expanded flux network (1) complements the other elements by determining monthly and annually averaged regional net uptake or release in typical ecosystems. The flux network will be able to define the systematic differences between flight days and non-flight days for the airborne profile measurements. Flux data can help account for CO_2 net exchange on days when analysis of the regional net exchange is not possible from atmospheric data, e.g.,during frontal passages or large weather events.

Improved carbon and land use inventories (4) provide a first-order check on the inferences from atmospheric measurements. By telling us where the carbon is going (or coming from),program element 4 also contributes significantly to the second part of Goal 1,to understand the underlying mechanisms that regulate the Northern Hemisphere terrestrial sink,and more generally, global terrestrial sinks and sources.The long-term terrestrial observations (7),process studies and manipulations (8) provide fundamental tools to develop new understanding of terrestrial sinks and sources.

Estimates of the Northern Hemisphere terrestrial carbon sink made from atmospheric CO_2 observations are very sensitive to the magnitude of the carbon sink in the North Atlantic and North Pacific. Oceanic observations (10) in the North Atlantic and Pacific Oceans thus provide important constraints on the Northern Hemisphere terrestrial carbon sink.

Modeling and synthesis (11) provide a large-scale check on inferred Northern and global fluxes when combined with global network (3) and airborne (2) data,and allow tests of our understanding through simulations of past and present conditions.

Goal 2: Program Elements 2, 3, 6, 9-11

The elements (9) global ocean measurements (surveys, time series, remote sensing),(10) a quantitative understanding of air-sea exchange processes,(2) airborne CO_2 observation program,and (3) global CO_2 monitoring network together address the first part of Goal 2: to quantify the oceanic uptake of CO_2. These elements provide direct long-term measurements defining sources and sinks on the scale of major ocean regions. A critically important task is to successfully integrate expanded observations of time series at key locations,observations of atmosphere-ocean exchange,periodic global ocean surveys, remote sensing of the oceans,large-scale airborne measurements over the oceans,and atmospheric data from island stations. The conceptual framework for interpreting these observations will be developed and tested in element (6), strategically planned regional observation experiments.

Ocean process studies and manipulations (10) tell us why the carbon is going (or coming from) major ocean regions and provide the basis for predicting long-term trends. Program elements (10) and (6) thus contribute significantly to the second part of Goal 2:to understand the mechanisms of oceanic uptake of CO_2.

Modeling and synthesis (11) provide large-scale checks on inferred oceanic and global fluxes,especially when exercised to provide global constraints using data from the global surface and airborne networks (elements (2) and (3). Models allow tests of our understanding through simulations of past disturbances,such as major El Niño-Southern Oscillation (ENSO) events.

Goal 3: Program Elements 1, 4, 5, 7, 11

The program elements (5) (reconstruct historical land use) and (4) (expand global terrestrial carbon and land use inventories) are specifically designed to address Goal 3: to determine the impact of historical and current land use. The expanded flux network (1),long-term terrestrial observations (7),and terrestrial process studies and manipulations (8) will provide integral checks and constraints on the interpretation of results from (4) and (5). Modeling and synthesis (11) will be the major tools bringing together the data and concepts developed by these program elements.

Goal 4: Program Element 11 (integrating elements 1-10)

The program element modeling and synthesis (11) represents the most comprehensive and integrating tool for Goal 4,projecting future atmospheric concentrations of CO_2. This goal is a major scientific undertaking,in which the models and analysis must be closely integrated with all other elements of the CCSP. To succeed, responsible agencies will need to develop a managerial framework with a unified vision of the program and with greatly enhanced mutual collaboration and strategic planning.

Goal 5: The Entire CCSP (all elements, integrated and coordinated)

Goal 5—developing the scientific basis for evaluating management decisions relating to CO_2 in many critical ways represents the culmination of the entire Carbon Cycle Science Plan. The ultimate measure of a successful carbon cycle research program will be found in its ability to provide practical answers to both scientific and societal questions.

Implementation Principles

Past experience with large-scale, multidisciplinary global change research programs (e.g. the TOGA Program) has demonstrated that a coherent,integrated approach to program implementation is essential for optimal execution and delivery of products designed to serve societal needs. The principles for successful implementation of the CCSP program, discussed in detail in Chapter 6 of the report,are:

- **A scientific vision shared by the broad community and by the participating agencies** to develop consistency and focus.
- **Shared programmatic responsibility** to insure coherence,coordination,and strategic pursuit of program goals.
- **Program integration** to bring together interdisciplinary aspects of the strategy.
- **Scientific guidance and review** to provide feedback and support to program managers,to help foster innovation and creativity, and to create an environment where program elements and goals evolve as new knowledge is obtained.
- **Links to international programs** to maximize the benefits from efforts in all countries.
- **Access to data and communication of research results** to insure timely communication of knowledge to the general public and to enhance the scientific utility of new knowledge.

With these principles in mind,the Working Group has recommended in Chapter 6 specific steps to establish a collaborative management structure for the Carbon Cycle Science Program,with strong interagency commitment to joint implementation of the program,including common development of requests for proposals and coordination review and funding activities. The program is built around a tripartite,collaborative management structure for integrated carbon cycle research consisting of a scientific steering committee (SSC),interagency working group (IWG),and Carbon Cycle Science Program office. The intent is to strengthen relevant federal agency activities by improved coordination,integration,coherence,prioritization, focus,and adherence to conceptual goals. The proposed structure will provide the basis for issuing interagency research announcements to stimulate a broad range of important new research,with agreed-upon goals,using a coordinated interagency merit review process of proposals and overall agency programs. The importance of fostering partnerships among Federal laboratories,the extramural research community, and the private sector is stressed,as is the need to communicate effectively the evolving understanding of carbon sources and sinks to the public and policy makers.

Initial Funding Priorities

Most of the program elements outlined above serve more than one of the major long-term and five-year goals. Again,the program requires a coordinated,integrated approach by the responsible agencies: the value of an integrated program will greatly exceed the return from uncoordinated program elements.

The individual program elements described in this plan, however, are not at equal stages of maturity and readiness. Some program elements represent intellectually-ready work that has been constrained by limited resources in the past and could begin immediately with a near-term infusion of funding. New technology enterprises, for example, have suffered disproportionately in the recent past due to such resource constraints. Since many of the program elements in the CCSP call for focused technology development prior to large-scale implementation, we recommend that a high priority be placed on funding those technology development efforts that have been deferred due to prior insufficient funding. More specifically, the following program elements should be considered as high priorities for initial funding:

- Both facility and technology development for the enhanced flux network,airborne sampling,and automated and streamlined ocean sampling for long time-series and underway measurements
- Airborne CO_2 monitoring programs,both dispersed weekly measurements and in support of regional studies
- An expanded and enhanced surface monitoring network for atmospheric CO_2
- Improved forest inventories (with carbon measurements a key focus and an explicit goal) and development of new techniques for remote sensing of aboveground biomass

- **Analysis of World Ocean Circulation Experiment/Joint Global Ocean Flux Study (WOCE/JGOFS) data for CO_2 uptake by the oceans**
- **New ongoing program of air-sea carbon flux and ocean inventory measurements**
- **Continued ocean process studies,such as air-sea exchange and enhanced manipulation experiments**
- **Enhanced development of Earth system modeling to include interactive carbon and climate dynamics.**

Chapter 1: Introduction

Rationale

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

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

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

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

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

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

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

Outline of the Research Program

The CCSP is designed to address two basic questions:

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

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

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

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

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

Sustained Observations

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

Table 1.1 US Carbon Cycle Science Plan

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

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

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

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

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

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

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

Manipulative Experiments

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

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

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

Model Development: Understanding and Predicting Critical Processes

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

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

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

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

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

Structure of the Plan

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

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

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

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

Chapter 4 describes the proposed Carbon Cycle Science Program.

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

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

Chapter 2: The Past and Present Carbon Cycle

Chapter 1 reviewed the two overarching scientific questions that the Carbon Cycle Science Plan (CCSP) is designed to address. This chapter turns more focused attention to the first of these two questions:

> ***What has happened to the CO_2 that has already been emitted through human activities (anthropogenic carbon dioxide)?***

Carbon cycle research relating to climate change fundamentally concerns three large scientific issues. The first is the natural partitioning of carbon among the "mobile" reservoirs—the ocean, atmosphere, and soil and terrestrial biosphere—partitioning that is influenced itself by climate change. The second issue is the redistribution of fossil fuel CO_2 within those same three reservoirs, and assessments of proposals to prevent emissions or sequester carbon through new technologies. The third issue concerns transfers between the terrestrial biosphere and the atmosphere induced by other human activities such as forest clearing and regrowth, the management of agricultural soils, and the feedback potential of anthropogenically driven changes in atmospheric chemistry and climate to alter these transfer rates.

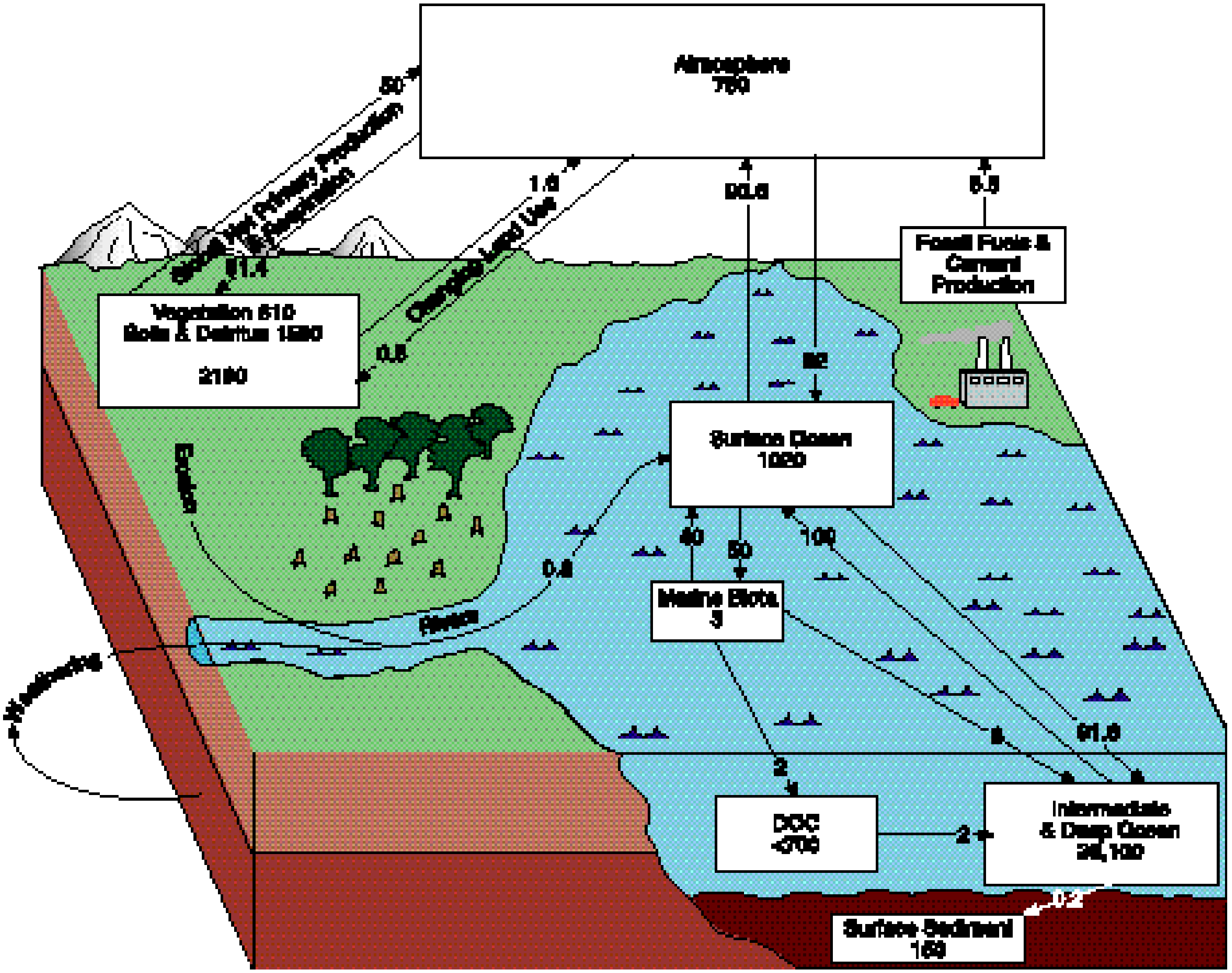
Historical changes in the quasi–steady state of the carbon system are clearly reflected in ice core and isotopic records, which also record the unprecedented changes caused by anthropogenic CO_2 emissions (Raynaud et al. 1993). The globally averaged atmospheric CO_2 mole fraction is now over 365 μmol/mol (or parts per million, ppm)—higher than it has been for hundreds of thousands of years. Atmospheric concentrations of CO_2 had remained between 270 and 290 ppm during the last several thousand years, but rose suddenly to the present level during the second half of the 20th century. This increase is coincident with the rapid rise of fossil fuel burning.

The modern rate of atmospheric CO_2 increase is accurately known from contemporary direct atmospheric measurements as well as from air stored in ice and firn (Battle et al. 1996, Etheridge et al. 1996). The Intergovernmental Panel on Climate Change (IPCC) assessment has summarized the state of scientific knowledge in this area (Schimel et al. 1995). During the decade of the 1980s, the rate of increase in the atmosphere was 3.3 ± 0.2 billions of metric tons (also called gigatons) of carbon per year (Gt C/yr). The next best-known piece of the puzzle is the rate of fossil fuel emissions, which was 5.5 ± 0.5 Gt C/yr during the 1980s (Marland et al. 1994). Thus, it is clear that on average a large fraction of the emitted CO_2 did not remain in the atmosphere. Conservation of mass implies that the missing emissions must have entered the ocean, the terrestrial biosphere, or both. The ocean carbon sink is the best known of these two remaining components of the carbon budget. According to the IPCC, the ocean absorbed 2.0 ± 0.8 Gt C/yr. This finding suggests that the global net terrestrial biosphere sink was only 0.2 ± 1.0 Gt C/yr. However, the estimated loss of carbon from the terrestrial biosphere due to deforestation is estimated to have been 1.6 ± 1.0 Gt C/yr. Thus, there must have been a compensatory storage of carbon in the terrestrial biosphere of 1.8 ± 1.6 Gt C/yr. The latter figure largely compensates for the land use source, so that the global net storage in terrestrial ecosystems was close to zero.

It has not been easy to arrive at these estimates. Regarding ocean uptake, if the CO_2 entering the ocean were mixed homogeneously, the cumulative increase in the total carbon content after 10 years at the rate of 2 Gt C/yr would only be 1.2 μmol/kg. This equals the detection limit of the currently best analytical techniques. Most of the CO_2 has been added to the upper few hundred meters, however. The signal is therefore detectable, but it must be extracted from large natural variations of up to about one to two hundred μmol C/kg. For this reason, until very recently, ocean uptake has been estimated using models whose parameters are calibrated against the penetration into the ocean of other tracers such as ^{14}C and tritium from nuclear tests, and chlorofluorocarbons.

Estimates of terrestrial carbon loss have been based on surveys of land use and changes in land use, above- and below-ground average carbon densities for ecosystem classes, and models of the development of carbon storage after disturbance, under human management, and during succession (e.g., Houghton et al. 1987). These assessments have varied greatly, as reflected in the range for tropical biomass destruction assessed by the IPCC to be 1.6 ± 1.0 Gt C/yr. Part of the problem in this evaluation is the great heterogeneity of carbon content on small spatial scales. But also, surveys have been difficult to compare because of incompatible definitions, different counting methods, the treatment of secondary forest growth, and similar reasons.

Estimates of terrestrial carbon uptake have been obtained from mass balance considerations such as those described above, which give a total uptake of 1.8 ± 1.6 Gt C/yr. Other estimates come from direct observations of forest carbon inventory changes (0.9 Gt C/yr in the Northern Hemisphere), models of NO_x fertilization (0.6 to 0.9 Gt C/yr), and CO_2 fertilization (0.5 to 2.0 Gt C/yr) (Schimel et al. 1995). There are strong indications that there is a large uptake in the Northern Hemisphere, but



The principal anthropogenic carbon fluxes, against the background of some of the main 'background'natural fluxes. The results are updated from the 1995 IPCC report and Schimel (1995) with updates from Sarmiento and Sundquist (1992) and Hansell and Carlson (1998).Fluxes shown are estimated averages for the decade of the 1980s. Where unbalanced fluxes are indicated (global primary production and respiration, land use and air-sea gas exchange) the imbalance reflects the anthropogenic fluxes. Note that this figure shows decadal average fluxes and we now know these fluxes to be quite variable from year to year.

the location,magnitude,and mechanisms of this uptake are poorly understood.

The following three sections summarize recent progress on the most uncertain components of the perturbations to the global carbon budget: (1) the terrestrial carbon sink,(2) the ocean sink,and (3) the land use source. Each section is concluded with a proposed major near-term (5 to 10 year) research initiative that will address the most compelling scientific issues identified, and which is also scientifically feasible and cost-effective.

The Terrestrial Carbon Sink

Perhaps the biggest recent change in thinking about the terrestrial sink has been that earlier estimates of enormous carbon losses from terrestrial ecosystems (Bolin 1977,Woodwell 1978) have given way to the idea that the terrestrial biosphere has been close to neutral with respect to carbon storage during the last decades. The observed destruction of forests appears to have been roughly compensated for by mechanisms of enhanced carbon uptake. Eight independent lines of evidence support this view:

1. The overall carbon budget estimated from the observed atmospheric increase and ocean uptake estimates using calibrated ocean models requires modest terrestrial uptake to satisfy mass balance (Bacastow and Keeling 1973,Oeschger et al.1975).
2. The smaller than expected north-south gradient of atmospheric CO_2, combined with data on the partial pressure of CO_2 in ocean surface waters,suggests that there is a large terrestrial CO_2 sink at temperate latitudes in the Northern Hemisphere (Tans et al. 1990). The sink compensates for, or is larger than, the estimated rate of carbon loss due to deforestation in the tropics.
3. The atmospheric ratio of oxygen to nitrogen has been declining due to the consumption of oxygen by fossil fuel burning. The ratio is decreasing as oxygen use is required by this fossil fuel burning,though perhaps slightly more slowly, indicating that there is no major net O_2 sink other than fossil fuel burning. There may even be a small net source,which would suggest that biological fixation of CO_2 may exceed rates of remineralization of organic matter (Battle et al.1996, Keeling et al.1996).
4. The existence of a large terrestrial sink at northern latitudes is supported by $^{13}C/^{12}C$ ratio measurements in atmospheric CO_2 (Ciais et al.1995a) and by measurements of the oxygen/nitrogen ratio (O_2/N_2) (Keeling et al.1996). At northern latitudes the $^{13}C/^{12}C$ and O_2/N_2 ratios are higher (relative to the Southern Hemisphere) than expected from fossil fuel burning alone. This suggests net uptake by photosynthesis,which (1) discriminates against uptake of ^{13}C relative to ^{12}C, leaving the atmosphere enriched in ^{13}C,and (2) produces O_2, enhancing the O_2/N_2 ratio.
5. A new technique is eddy covariance,which can measure vertical transport in a turbulent atmosphere. Flux measurements obtained by this technique in different ecosystems have demonstrated the ability of some forests to act as significant net sinks for atmospheric CO_2 (Wofsy et al.1993,Baldocchi et al.1996). However, the number of such measurements that is available is too limited to draw any strong conclusions.
6. The increase in amplitude of the seasonal cycle of atmospheric CO_2, and especially the earlier onset of the summer photosynthetic drawdown,is consistent with net uptake by temperate land ecosystems (Myneni et al.1997,Randerson et al.1997).
7. Recent forestry surveys in various regions of the Northern Hemisphere also tend to indicate net carbon uptake,but not as large as the atmospheric data seem to imply (Dixon et al.1994).
8. During earlier decades (1970–1990) the measured change in the oceanic $^{13}C/^{12}C$ ratio indicates relatively little net uptake by the terrestrial biosphere when analyzed in the context of changes in atmospheric concentrations (Quay et al.1992).

The storage of organic carbon in terrestrial sediments may be much more important than previously recognized (Stallard 1998). Carbon storage through erosion may sequester carbon if significant amounts of eroded carbon are stored in sediments where they will decompose slowly, and if regrowth of vegetation on eroded lands replaces the lost carbon. This sink,combined with expansion of rice agriculture and postulated net storage of carbon in rice paddy soils,could amount globally to 0.6-1.5 Gt C/yr (Stallard 1998).

It is noteworthy that five of the above arguments are based entirely or partly on the atmospheric measurement of fluxes,either directly or as deduced from spatial patterns of the concentration of gaseous species. The first argument is based on a global mass balance involving the ocean,and the first of the flux arguments makes use of air-sea fluxes. Estimates of aboveground terrestrial biomass are being made routinely, but two-thirds of the global terrestrial carbon is in soils,and it has been hard to obtain accurate inventories,let alone temporal change data for this pool. It is encouraging that the evidence for terrestrial sinks is internally consistent because each of the approaches has its own problems,to be briefly discussed next.

Interpreting observations of the CO_2 mole fraction in terms of surface sources and sinks requires atmospheric transport models that portray large-scale circulation

accurately, and that also parameterize subgrid-scale mixing correctly. The recent atmospheric transport model comparison study (TRANSCOM) exercises show that significant improvement in both respects is sorely needed,and that the atmospheric boundary layer is of particular importance (Law et al.1996,Denning et al.1999). Because the atmospheric signature of low-latitude sources is weak due to vigorous vertical mixing,and because there are no applicable observations in some important areas (such as tropical forests),the models currently work roughly as follows. Sources and sinks are derived from observed concentration patterns with some degree of confidence for the temperate and high latitudes,and those for low latitudes then follow essentially from global mass conservation. Calibrations of certain aspects of the transport with other tracers with "known"sources,such as CFCs, ^{85}Kr, or SF$_6$, are useful,but fail in that the strong diurnal and seasonal cycles of CO$_2$ sources are not included,and also because these tracers have strong sources in the tropics.

The interpretation of the isotopic data is subject to substantial uncertainty. The main source of error is the contribution of purely isotopic exchange,often called the isotopic disequilibrium flux,which may occur with or without an accompanying net exchange of total carbon (Tans et al.1993). A better determination of the rate of air-sea gas exchange is especially important to pin down the isotopic disequilibrium flux between the ocean and atmosphere. The isotopic disequilibrium between the atmosphere and the terrestrial biosphere depends on the average age of the respiratory carbon flux,which should be better known as well. This age is important because older biomass was fixed during times that the atmosphere was less depleted in ^{13}C than today. In interpreting atmospheric ^{13}C/^{12}C trends, relatively small uncertainties in isotopic disequilibrium between the atmosphere and ocean translate into large uncertainties in the partitioning of the total sink between ocean and land (e.g.,an uncertainty of only 0.1 per mil,or parts per thousand,in isotopic disequilibrium gives an uncertainty of 0.5 Gt C in partitioning). Furthermore,the isotopic signature of terrestrial primary productivity, strongly influenced by the relative proportions of the C3 and C4 photosynthetic pathways,needs to be better defined.(Fung and al.1997,Lloyd and Farquahar 1994). The isotopic fractionation during C4 photosynthesis is not much different from that of air-sea exchange.

The atmospheric oxygen budget may be subject to uncertainties concerning decadal variations in the ventilation of deeper, oxygen-poor waters of the ocean. It is reassuring that two completely different analytical techniques give similar results (Bender et al.1994, Keeling and Shertz 1992).

The new micrometeorological (eddy-covariance) flux measurement methods have been developed to measure ecosystem exchange of trace gases on a spatial scale of hundreds of meters (Wofsy et al.1993,Baldocchi et al. 1996,Goulden et al.1998). There is also a network of about 10 U.S.Department of Agriculture (USDA) Agricultural Research Service grassland sites (tallgrass, mixed grass,shortgrass steppe,intermountain,and shrublands) equipped with Bowen Ratio/Energy Balance (BR) towers that are monitoring CO$_2$ and H$_2$O fluxes. In grasslands,BR systems work well and are less relatively expensive. Such measurements are used in conjunction with known disturbance history, and with climatic,plant physiological,ecological,and soil data,to investigate mechanisms responsible for the uptake or loss of carbon for whole forest ecosystems,including soils.

The manageable spatial scale facilitates the search for flux mechanisms,but makes it necessary to test extrapolations to regional scales with other methods. Relationships between fluxes and climatic variables have been found (Goulden et al.1996,Goulden et al.1998). When turbulence is well developed,often during the day, the eddy-covariance method is well demonstrated,but at night under stable conditions,the measurements are less reliable and heterotrophic respiratory fluxes (fluxes from non-photosynthetic organisms) may be underestimated. This problem can be partially circumvented by selecting measurement times when conditions for the method are favorable,although this introduces the danger of aliasing, or obtaining biased data because of non-representative sampling. An explicit quantification of the spatial error associated with the measurement of net ecosystem production (NEP) by the eddy flux method will allow a quantitatively defensible scaling-up from local to regional analyses of NEP. This achievement will require replication of eddy flux towers at both local and regional scales. The number and spacing of such towers is a topic for research,but techniques are available that can be applied to the task (e.g.,Harrison and Luther 1990).

A central theme of research on the terrestrial carbon sink over the last decade can be formulated as the following hypothesis:

Hypothesis 1: There is a large terrestrial sink for anthropogenic CO$_2$ in the Northern Hemisphere.

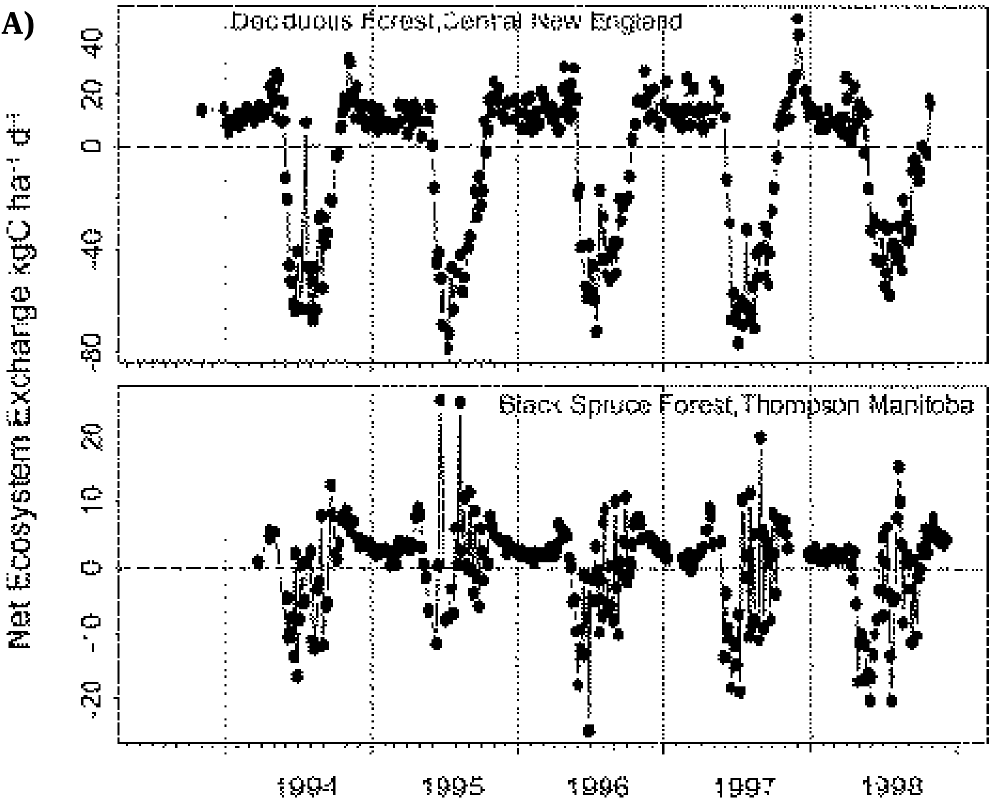
This hypothesis is known by the term the Northern Hemisphere Terrestrial Carbon Sink or "Northern Land Sink."

The suggestion that there is such a carbon sink is strongly supported by a wide range of observations,data analysis,and modeling studies,many of which have been discussed above. The magnitude of this sink was estimated to be on the order of 1.5 + 1.0 Gt C/yr for 1980-1989 (Schimel et al.1996),and as having increased to >2.5 Gt C/yr over the last decade,making it a major contributor to

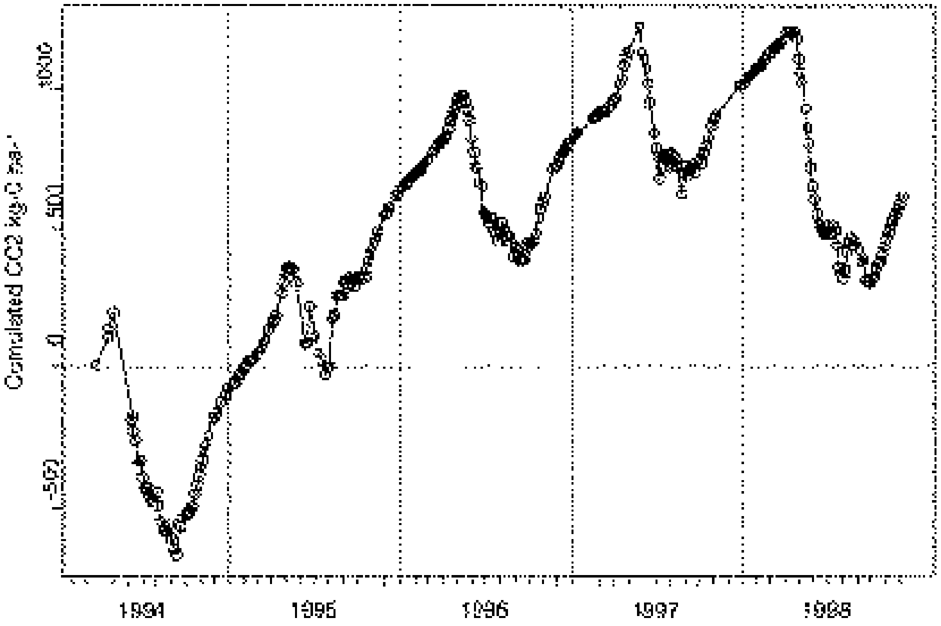
(A) Daily net ecosystem exchange for Harvard Forest, Central New England (top) and the BOREAS site, Manitoba, Canada (bottom). These data are illustrative of the rich information to be gained from flux towers. Both forest sites show the pattern of carbon exchange throughout the year, with carbon uptake occurring during the growing season (negative values) and release during the winter (positive values). Differences between sites can also be noted: the growing season starts earlier at the BOREAS site, yet the forest there is less efficient overall at storing carbon. Data from towers can also be analyzed in conjunction with temperature and precipitation patterns, for example, to determine the long-term responses of major ecosystems to climate variability.

(B) Overall, the BOREAS site was a net source of carbon to the atmosphere during 1994 to 1998, despite a longer growing season than average. This result is partially due to the release of carbon from cold soils starting earlier in the year, around August, and persisting throughout the winter months.

(A)



(B)



perturbations of the carbon budget. However, in addition to the large uncertainty in the magnitude of this sink, its location and interannual variability, and the mechanisms that cause it are all highly speculative.

One important issue to address in this context is the role played by CO_2 and nitrogen fertilization in the current carbon balance.

These two types of fertilization may stimulate biogenic uptake of carbon, thus providing a carbon sink. They are generally believed to be most important at mid-northern latitudes (Schimel et al. 1996), but these mechanisms must be further quantified and their possible future roles assessed. Ecosystem manipulations, including studies with elevated CO_2 and nitrogen additions, and consideration of a range of potentially interacting factors, will provide insights into physiological, ecological, and biogeochemical processes underlying the carbon storage in the terrestrial biosphere. These same points apply to controlled applications of ozone. Projects investigating these processes are coordinated by the Global Change and Terrestrial Ecosystems (GCTE) project of the International Geosphere-Biosphere (IGBP) Program. The results from these experiments will need to be extrapolated from the experimental scale to larger regions, requiring understanding of the scale-dependence of the processes and their interactions.

Extending the results of these experiments from the local to regional and global scales will require four components. First, the experiments must be designed to provide access to the underlying mechanisms that control the scaling. Second, the experiments must be repeated in enough ecosystems to capture the full range of mechanisms. Third, the regions where the responses are estimated must be sufficiently characterized to support the extrapolation. And fourth, the models used for the scaling must be robust. The terrestrial biosphere is too heterogeneous to be characterized by simple extrapolation of a reasonable number of experiments, but the processes that regulate it are uniform enough to be effectively handled in mechanistic models.

Another fundamental issue in this area is how carbon storage is affected by changes in land use, disturbance, and vegetation structure and composition.

Carbon storage in vegetation is being continually altered by land use and disturbance (e.g., fires) and with the recovery of vegetation from historic land use. In addition, the competitive relationships among species and their interdependence are changing owing to multiple causes, climate change among them. A change from grassland to forest, for example, would certainly change carbon storage. Changes in vegetation assemblages are likely to be important drivers for carbon storage or release on decadal and longer time scales. The development of dynamic global vegetation models (DGVMs) is beginning to accelerate, and they will likely become important tools in understanding the future carbon cycle.

The development of measurement techniques and methods of data analysis have placed us in a position to propose a major new near-term CCSP initiative with the following goal:

> Goal 1: Establish accurate estimates of the magnitude of the potential Northern Hemisphere terrestrial carbon sink and the underlying mechanisms that regulate it.

Large carbon sinks have been hypothesized to be associated with a variety of terrestrial phenomena (for example, greater erosion and sediment deposition, land use changes, CO_2 fertilization, and length of the growing season). Clearly, additional observations and improved models of terrestrial processes are needed.

Such terrestrial studies cannot be interpreted in isolation. The Northern Land Sink hypothesis directly suggests additional linked hypotheses and observations. As research on land clarifies the distribution of particular hypothesized sources and sinks, parallel improvements will be required in the temporal and spatial resolution of atmospheric and oceanic observations and models. For example, a direct corollary of the Northern Land Sink hypothesis is the hypothesis that there is a large oceanic carbon sink in the Southern Hemisphere. This sink is hypothesized because the global CO_2 budget requires a large ocean sink somewhere, and Northern Hemisphere ocean CO_2 uptake appears to be relatively small based on the atmospheric ^{13}C and ocean surface pCO_2 (partial pressure of CO_2) measurements (Tans et al. 1990). These are the same measurements and arguments that led to the hypothesis of the Northern Land Sink.

The Ocean Carbon Sink

The total capacity of the ocean to dissolve anthropogenic CO_2 is mainly a chemical property and can be calculated by considering the appropriate chemical equilibria. The primary challenge to current understanding of the ocean carbon sink is in estimating the rate at which anthropogenic CO_2 dissolves in the ocean. It is necessary to know the present rate of dissolution and how climate change and changes in the biological pump will affect the uptake rate and ultimate capacity in the future. A separate, but also important, problem is to determine the spatial distribution of air-sea CO_2 fluxes, a factor that is a major constraint on inverse modeling analyses such as those discussed in the previous section. Each of these issues is discussed in turn, beginning with present knowledge of the rate of ocean carbon uptake and the spatial distribution of carbon sources and sinks. Chapter 3 additionally discusses how climate change and related changes in the biological pump might affect the rate of uptake in the future.

Ocean carbon uptake has been estimated by considering the change in carbon inventory through time, the magnitude of the air-sea CO_2 flux, and the magnitude of carbon transport within the ocean. The estimates used by the IPCC in constructing global carbon budgets are based primarily on inventory calculations using ocean circulation models calibrated or validated with tracer observations (e.g., bomb radiocarbon; see Schimel et al. 1996). The magnitude of these estimates has remained consistent over almost three decades of continuous testing with new models and tracer data. Nevertheless, the estimates are typically reported as having an uncertainty of ± 40 percent. The large uncertainty reflects the fact that tracer measurements are imperfect analogs for fossil fuel CO_2 and have been relatively sparse until quite recently.

Further, ocean models have limitations in their representations of ocean circulation and mixing. An important goal of research over the last decade has thus been to expand the tracer data set and improve ocean carbon models. The skill of ocean carbon cycle simulations is directly linked with improving models of the physical transport of the underlying ocean general circulation. Considerable success has been achieved in the last decade through better parameterization of mesoscale eddy mixing processes (Gent et al. 1995).

Additionally, there has been a major effort to develop methods and obtain measurements to assess the oceanic uptake directly or indirectly from dissolved inorganic carbon (DIC) observations.

One of the most important advances has been the acquisition of a new global data set of ocean tracer and carbon system observations of unprecedented accuracy through the World Ocean Circulation Experiment/Joint Global Ocean Flux Study (WOCE/JGOFS). The tracer measurements, together with the rapid improvement of ocean circulation models based on these and other WOCE observations, are expected to lead to improved model uptake estimates. DIC data sets accurate to 1 to 2 mmol/kg, which is equivalent to 1 to 2 years' uptake of anthropogenic CO_2 in near-surface waters, are now available for hydrographic transects representing most of the world's ocean. The $^{13}C/^{12}C$ of DIC was measured on every sample collected for Accelerator Mass Spectrometry (AMS) ^{14}C measurement during WOCE, which yields the first oceanwide high-quality $^{13}C/^{12}C$ data set (±0.03 parts per thousand). These new data sets are already significantly improving knowledge of the distribution of inorganic carbon in the ocean.

A parallel occurrence has been the development of methods to estimate the oceanic uptake of carbon by direct analysis of the DIC observations. Three complementary methods have been proposed in order to constrain (or set the estimated outside boundaries of) the oceanic uptake of anthropogenic carbon directly from ocean data: (1) repeat or time-series observations of water column DIC to measure the current rate of change of the DIC inventory; (2) "preformed CO_2" methods to calculate the integral change of the DIC inventory from the pre-industrial period to the present; and (3) air-sea CO_2 flux methods to measure the present global net flux into the ocean.

One of the most important needs is to gain a better understanding of the spatial patterns of surface ocean CO_2 concentrations and their variability. Seasonal and interannual variability of CO_2 concentrations in the surface ocean are one to two orders of magnitude greater than their annual increase due to uptake of anthropogenic carbon (e.g., Bates et al. 1996, Winn et al. 1994). Because the signal to be detected is much smaller than this variability, it takes a decade or longer to begin to see anthropogenic trends. In addition, the seasonal and interannual variability in CO_2 concentration gives information on how the carbon cycle functions, and can be used in conjunction with other methods to help understand regional and global patterns of carbon uptake. A very promising development of the last decade is new instrumentation that will make it possible to measure pCO_2 (DeGrandpre et al. 1995, Friederich et al. 1995, Goyet et al. 1992, Merlivat and Brault 1995) and other properties from moorings. The CCSP envisions that moorings with these capabilities will allow establishment of many more time-series stations at feasible cost in otherwise remote locations.

An alternative to long-term measurements is to use methods of analyzing the data that permit identifying the anthropogenic carbon component within the huge background signal and variability that arises from seasonal and interannual change. The "preformed CO_2" method uses the correlation of data on carbon, nutrients, oxygen, and physical variables to separate natural variability from changes due to uptake of anthropogenic CO_2 (see Gruber et al. 1996). In a second method, multiple linear regression coefficients are calculated for carbon versus other variables (Wallace et al. 1995). These coefficients are used to correct for the natural variability between measurements made at two different times, thereby isolating the change due to addition of anthropogenic carbon. The two methods are somewhat independent and address different time scales. The preformed CO_2 method gives an estimate of the oceanic uptake of anthropogenic CO_2 since pre-industrial times; the multiple linear regression method has been applied to estimate the increase in oceanic CO_2 concentration between the Geochemical Ocean Sections program (GEOSECS) expeditions and WOCE/JGOFS, spaced about two decades apart (Wallace et al. 1995). Syntheses of Atlantic Ocean (Gruber 1998) and Indian Ocean (Sabine et al. 1999) DIC data from WOCE/JGOFS, analyzed

by the preformed CO_2 method, show large regional discrepancies between observed and modeled penetration of anthropogenic carbon. It is already clear that the observed penetration of anthropogenic CO_2 can provide, through detailed comparison with models, the basis and impetus for improving models of oceanic CO_2 uptake.

The flux of carbon between surface waters and the atmosphere can also be constrained using data of the partial pressure difference between the air and the water, ΔpCO_2, combined with estimates of the gas exchange coefficient (Takahashi et al. 1997). Of course, this flux includes both a natural and an anthropogenic component. The value of the technique lies primarily in determining the spatial distribution and temporal variability of air-sea CO_2 fluxes. It is particularly useful where the signals are large, as in the North Atlantic and Equatorial Pacific, or in the contrast between El Niño and non–El Niño years.

One currently weak link in the air-sea CO_2 flux approach is poor understanding of the kinetics of the process of air-sea gas exchange (see Wanninkhof 1992). The degree of nonlinearity in the relationship between the gas-exchange and wind speed is poorly understood, particularly at high wind speeds where bubble effects may become important. For instance, if the exchange velocity were to depend more strongly than is currently believed on variables correlated with wind speed, our estimates of fluxes in regions with high wind speeds, such as the high latitudes, would increase. It is time to determine through measurements a much better parameterization of the exchange velocity, so that observations of the atmosphere can be truly informative for oceanographic issues, and vice versa. Surface sources and sinks drive large-scale gradients of atmospheric CO_2 concentrations that could be, for example, an important constraint on CO_2 uptake by the Southern Hemisphere ocean poleward of about 30°S. As atmospheric transport models continue to improve, this constraint will become more compelling as a major input for inverse models of atmospheric CO_2 observations.

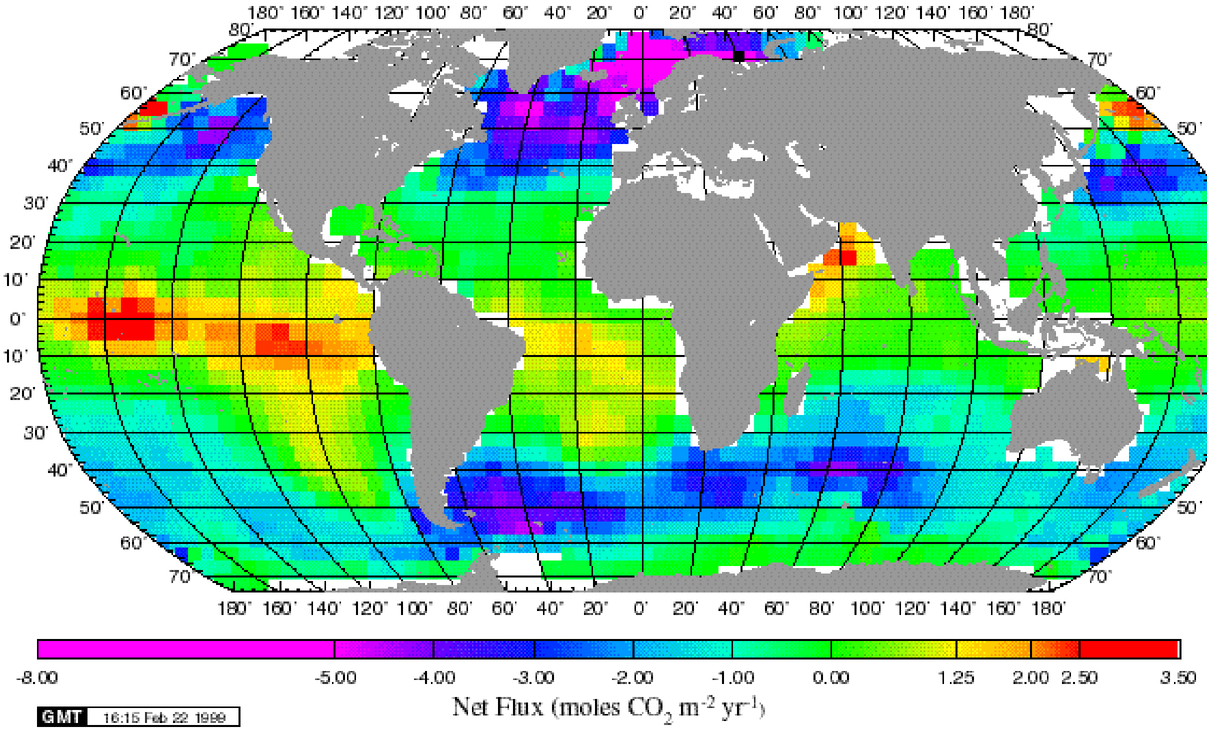
Another analysis approach that makes use of oceanic DIC data is estimation of horizontal carbon transport within and between ocean basins (e.g., Brewer et al. 1989, Holfort et al. 1998). This approach permits separate assessments of the transport of natural and anthropogenic carbon components in the ocean. The air-sea flux can be inferred from the divergence of the horizontal transport, which would provide a means of coupling the ocean inventory method with the surface ΔpCO_2 method. While horizontal carbon transport estimation is only starting to be implemented in the ocean, the tremendous improvement in ocean DIC measurements and the large new data set gathered by WOCE/JGOFS show great promise for the near future.

Knowledge of the spatial distribution of the air-sea CO_2 flux varies greatly from one region to another. The North Atlantic is perhaps the best-constrained region. Models, observation-based estimates of air-sea flux, and estimates of the ocean inventory of anthropogenic carbon all converge on similar answers (Gruber 1998, Gruber et al. 1996, Sarmiento et al. 1995, Takahashi et al. 1997). However, difficulties remain in reconciling these estimates with independent estimates of the net meridional transports of carbon (Brewer et al. 1989; Broecker and Peng 1992; Holfort et al. 1998, Keeling and Peng 1995). The North and Equatorial Pacific Ocean have not been as thoroughly explored, though the measurements that are available show reasonable consistency. The rest of the world is mostly very poorly constrained.

Analysis of CO_2 exchange in the Southern Ocean Ocean (waters around Antarctica poleward of approximately 50°S latitude) is especially difficult because of the high spatial and temporal variability of its properties and the difficulty of working in that region. The Southern Ocean appears to be especially important to levels of atmospheric CO_2. Deep ocean waters are mixed to shallow depths there, providing one of the major pathways for the uptake of anthropogenic CO_2 into the deep ocean. Wind speeds are high, enhancing rates of air-sea CO_2 exchange. The dissolved macronutrients available at the surface for plant growth are significantly underutilized (e.g., Falkowski et al. 1998), suggesting a capacity for enhanced uptake of CO_2 by photosynthesis. Macronutrients may be underutilized for several reasons; there is less sunlight at high latitudes, biological processes are slower because of low temperatures, there is less time for biota to develop because surface water is mixed back into deeper layers more quickly, and necessary micronutrients such as iron may be less available (Baar et al. 1995, Falkowski 1995). All these factors may be affected by climate change.

Models of the oceanic uptake of anthropogenic CO_2 (e.g., Sarmiento et al. 1992) predict that a substantial amount is being absorbed south of 30°S. Yet there are large discrepancies between the observations and the models of oceanic CO_2 uptake in the high southern latitudes. Recent survey data for the southern Atlantic (Gruber 1998) and Indian (Sabine 1999) oceans show surprisingly little uptake in these areas. The (sparse) atmospheric data also point toward a small Southern Ocean sink. Recently, observations of a composite atmospheric tracer, effectively equal to the sum of atmospheric O_2 and CO_2 concentrations, were compared with predictions from three different ocean models (Stephens et al. 1998). The largest discrepancy between models and observations was found over the Southern Oceans, suggesting that the models may misrepresent exchanges of O_2 and CO_2 in this region.

There are few constraints on the temporal variability of the air-sea flux of CO_2. The Equatorial Pacific is being monitored reasonably well (e.g., Feely et al. 1995, Feely



Distribution of the mean annual sea-air pCO_2 flux (partial pressure of carbon dioxide, moles $CO_2/m^2/yr$) over the global oceans estimated for a reference year 1995. These data show the global pattern of surface CO_2 uptake and release by the ocean. Note that the major sink regions are the North Atlantic and Southern Oceans, and that the Equatorial Pacific is a large source region in a typical year. This map does not reflect the variability due to El Niño/Southern Oscillation (ENSO) cycles, for example, which can alter the size of the ocean sink on an interannual basis. This map has been constructed based on about 2 million measurements of sea-air pCO_2 difference made over the past 25 years. These values have been corrected to a reference year of 1995 for the increase in pCO_2 of the atmosphere and surface ocean water that has occurred since the measurements were made, and the measurements made during El Niño years in the equatorial Pacific have been excluded. Thus, the map represents a climatological mean for non-El Niño conditions. The net CO_2 flux across the sea surface has been computed using the effect of wind speed on the CO_2 gas transfer coefficient formulation by Wanninkhof (Equation 1, 1992) and the mean monthly wind speed of Esbensen and Kushnir (1981). The numerical method used for the construction of these maps has been described in Takahashi et al.(1997) and Takahashi et al.(in press). The map yields an annual CO_2 flux for the oceans of 2.2 PgC/yr, in which the North Atlantic (N of 14°N) and the Southern Ocean (S of 50°S) are major CO_2 sink areas taking up 0.8 and 0.6 PgC/yr respectively.

et al.1994, Feely et al.1996),and the ongoing feasibility studies to instrument the ATLAS moorings of the Tropical-Atmosphere-Ocean (TAO) array with CO_2 sensors are an important development (Friederich et al.1995). There are also two time-series measurements near Bermuda and Hawaii (e.g.,Bates et al.1996, Winn et al.1994). However, most of the ocean is unknown with regard to the temporal variability of CO_2 fluxes. Analyses of stable carbon isotopes in atmospheric CO_2 suggest that sinks in both the ocean and the terrestrial biosphere vary by large amounts from year to year (Keeling et al.1989, Keeling et al.1995a, Ciais et al.1995b, Francey et al.1995). No oceanic mechanism has been developed to explain such conspicuous variability. A related need is for the calculation of temporal changes in oceanic carbon uptake on the global scale. The global oceanic uptake rate of CO_2 is currently not known to better than about ± 40 percent. This knowledge is not sufficient to determine whether the ocean carbon uptake rate has increased or decreased over the past few decades. Moreover, uncertainties of this magnitude limit the ability to constrain the historical global CO_2 budget using the record of atmospheric CO_2 concentrations over the last 200 years.

However, the problem of understanding the ocean should not be viewed as simply a comparison of current and future DIC "snapshots." It is also important to identify and understand the mechanisms that might cause future changes in the ocean carbon sink.

One of the most important issues to address is which mechanisms of ocean circulation that significantly shape anthropogenic CO_2 uptake are likely to be affected by a changing climate?

Changes in ocean circulation resulting from climate change will immediately affect the way anthropogenic

CO_2 is exchanged between the atmosphere and the ocean. The behavior of the present and past ocean, including the response to temporal variability, provides the strongest clues to the links between ocean circulation and atmospheric CO_2.

An additional question is how is the biological pump affected by the thermohaline circulation and changing climate? And is there any evidence that the C/N and C/P ratios of marine production are changing,or that “preformed” nutrients (the nutrient concentration of water that has cooled and sunk to depth) are changing?

CO_2 exchange between the ocean and atmosphere naturally occurs at the ocean surface. Photosynthesis by organisms in the upper, sunlit layer of the ocean keeps the CO_2 concentration of the surface waters substantially lower than that of deep waters. It does so by producing organic carbon that is exported to the deep ocean where it is converted to DIC. The excess deep ocean DIC that thus results is analogous to the organic carbon stored in soils, in that it is isolated from the atmosphere. Without photosynthesis in the ocean, and assuming no other surface changes due to organisms (such as calcification),the excess deep ocean DIC would escape to the atmosphere and atmospheric CO_2 concentration would be between 900 and 1,000 ppm (the current value, again, is 365 ppm). If, on the other hand, photosynthesis continued everywhere until all of the plant nutrients were fully depleted in all surface waters,atmospheric CO_2 would be between 110 and 140 ppm. (The actual pre-industrial atmospheric CO_2 concentration was 280 ppm.) These figures indicate the great power of the oceanic biological pump.

Long-term surface ocean time series that include detailed biogeochemical and CO_2 measurements are improving the mechanistic understanding of processes that affect ocean-atmosphere carbon uptake and partitioning. Time-series data sets from Bermuda and Hawaii are being used to develop model parameterizations of ocean biogeochemical processes affecting the ocean carbon cycle (Doney et al. 1996, Fasham 1995). Such time series are also increasingly being used as test beds for novel high-resolution measurement instruments. Notable findings from the time-series sites include an increased awareness of the complexity of the ocean’s nitrogen cycle (Karl et al. 1997). This finding has the potential to alter the view of the sensitivity of atmospheric CO_2 concentrations to biological processes in the ocean (Falkowski 1997). On longer time scales, ocean biology can have an impact on the atmosphere (see the following chapter). The time-series sites are among the few locations where seasonal variations in upper ocean $^{13}C/^{12}C$ ratios are measured (Bacastow and Keeling 1973). Such time-resolved information is critical for correctly interpreting the large “snapshot” data sets collected along ocean transects.

To summarize, our current understanding is that, as atmospheric CO_2 levels increase through time, the ocean responds by dissolving more CO_2 in the surface mixed layer, and by mixing the CO_2-enriched surface waters downward through exchange with deeper waters. The possibility also exists that changes in the biological pump may affect the future air-sea balance of CO_2. If our present understanding of these processes is correct,the ocean should have the capacity to absorb large quantities of anthropogenic CO_2 over time scales of decades to millennia. Most model simulations of future atmospheric CO_2 levels assume that present-day factors controlling plant physiology, air-sea exchange, and ocean mixing will remain constant into the future (Schimel et al. 1996). However, as previously noted, these assumptions have been questioned, especially because of the potential for significant responses to climate change. Air-sea gas exchange, ocean circulation, and marine photosynthesis are susceptible to changes in air temperatures,wind velocities, sea surface roughness, and wind and precipitation patterns. The most powerful tool for understanding the mechanisms underlying potential changes is in studying long-term trends and shorter-term fluctuations. Given all these considerations, a major CCSP initiative in ocean carbon cycle research is proposed to achieve the following:

Goal 2: Establish accurate estimates of the oceanic carbon sink and the underlying mechanisms that regulate it.

Land Use

One of the main driving factors in determining the Northern Land Sink may be land use,both past and present. For example,there has been widespread reforestation since 1900 in the eastern United States following the movement of the center of agricultural production toward the Midwest. Also,less agricultural land is needed today than during the first half of this century;the productivity of agriculture has improved so much that double the output can be produced on half as much land. The heavy use of fertilizer, together with improved tilling practices,may also lead to increased stores of organic matter in soils.

The carbon balance in the tropics also affects estimates of the magnitude of the Northern Land Sink. As pointed out before,the major constraint on the estimated magnitude of the global terrestrial carbon sink comes from two numbers. The first is the estimate of a global net terrestrial uptake of 0.2 ± 0.9 Gt C/yr for the period from 1980 to 1989. This number is obtained from calculating fossil fuel

***Top panel:* Managed forests in the Coast Range of Oregon. Conversion of old-growth forests to managed plantations in the Pacific Northwest has reduced the store of carbon to less than 25-35% of the maximum value in the last century. This has resulted in a substantial loss of carbon to the atmosphere. Altering management by increasing the interval between harvests and/or removing less carbon each harvest would "re-store" much of this carbon over the next century.**

***Bottom panel:* Deforestation in tropical regions has released a substantial amount of carbon in the last 50 years. Here the moist tropical forest of Los Tuxlas in Veracruz State, Mexico has been converted to maize and pasture agriculture. This conversion has reduced carbon stores on these sites at least 5-fold.**

emissions minus atmospheric growth and ocean uptake. The second number is the estimate of 1.6 ± 1.0 Gt C/yr released to the atmosphere from tropical deforestation. The difference between these numbers gives a required terrestrial uptake of 1.8 ± 1.4 Gt C/yr (Schimel et al. 1996), much of which appears to be in the Northern Hemisphere. If the net carbon flux from changes in tropical land use were at the lower limit of 0.6 Gt C/yr, the Northern Land Sink would drop to 0.8 Gt C/yr. Maintaining the observed north-south gradient of CO_2 in the atmosphere would require that the Southern Ocean would have to be a smaller sink than currently estimated. The recent land use estimate of Houghton et al.(1998) yields 2.0 ± 0.8 Gt C/yr for the tropical land use source. This value would require a compensatory terrestrial carbon sink of 2.2 Gt C/yr as well as a larger Southern Ocean carbon sink. Gaining more certainty in the land use numbers will reduce uncertainty in other contributing components of the Northern Land Sink,such as the fertilizing effects of rising atmospheric CO_2 and N deposition.

The uncertainty of net carbon flux from land use stems largely from incomplete and often incompatible databases used to compile land use changes,and from the lack of knowledge of carbon fluxes associated with specific activities. These points are particularly true of tropical areas and for land uses involving economically nonproductive ecosystems (i.e.,nonproductive in a direct sense),such as wetlands, riparian forests,and natural grasslands. For example,Houghton et al.(1998) notes that no reliable data exist for Latin America on that portion of the loss of agricultural land to degraded land that is not recovering to forest. This situation has forced the omission of such land from the calculation of net carbon flux. The same is true for land subjected to shifting cultivation and the harvest of wood in Sub-Saharan Africa.

Tests of the Northern Land Sink hypothesis will thus require the further development and refinement of data sets on historical land use changes,carbon stores per unit area,and models that can use this information. The goal should be to acquire and analyze accurate global inventories of highly fractionated land use change. Doing so, however, requires a concerted effort to develop high-quality, spatially explicit,long-time-series data sets on land use. These data sets should be constructed from a variety of sources,including high-resolution, remotely sensed imagery, explicit data on land use going back many decades, government publications, research data,and reconstruction using proxy information. Side-by-side comparison of population change and measured rates of deforestation,where the data coexist,lends confidence to the reconstruction of rates of deforestation using relatively well-defined changes in population as the predictor.

A major new CCSP initiative is therefore proposed to meet the following goal:

Goal 3: Establish accurate estimates of the impacts of historical and current land use patterns and trends on the evolving carbon budget at local to continental scales.

Chapter 3: Predicting the Future Carbon Cycle

The previous chapter addressed the first of the two overarching questions that the Carbon Cycle Science Plan (CCSP) must attempt to answer. In this chapter, we turn to the second of the two fundamental issues for carbon cycle research:

> ***What will be the future atmospheric carbon dioxide concentrations resulting from both past and future emissions?***

The research program outlined in this report will ultimately be measured by its ability to provide reliable estimates of future atmospheric CO_2 concentrations under different conditions. Only with such knowledge will it be possible to assess alternative scenarios of future emissions from fossil fuels, effects of human land use, sequestration by carbon sinks, and responses of carbon cycling to potential climate change. Thus, the foremost reason for additional research is to develop the ability to predict responses of the global carbon cycle to various types of change. The CCSP must be integrated in the form of a rigorous and comprehensive effort to build and test models of carbon cycle change, to evaluate and communicate uncertainties in alternative model simulations, and to make these simulations available for public scrutiny and application. The models must also be capable of evaluating alternative scenarios for management of the carbon cycle.

There are grounds for optimism that in coming years the fate of CO_2 in the ocean can be ascertained with reasonable accuracy. The global mass balance among emissions, atmosphere, ocean, and terrestrial biosphere ensures that a better quantitative estimate of ocean uptake also improves the estimate for changes in terrestrial storage, if only in very coarse geographical detail. Direct measurements of terrestrial inventories and fluxes, in conjunction with atmospheric measurements and models, will help to refine the geographical details.

Unfortunately, improved knowledge of the environmental fate of historical CO_2 emissions cannot by itself give us confident predictions of future atmospheric CO_2. The CO_2 concentration trajectories calculated by the Intergovernmental Panel on Climate Change (IPCC) for scenarios of fossil fuel burning assume that the future carbon cycle will continue operating exactly as it is thought to have operated in the past. This assumption is not likely to be correct.

There is a fundamental difference between the ocean and the terrestrial biosphere for policy decisions relating to greenhouse gases. The ocean remains the biggest long-term player in the carbon cycle, and any research program that neglects the ocean is doomed to be nearly irrelevant for policy. However, direct human interventions in the ocean carbon cycle have thus far been minimal. Furthermore, any future human interventions, such as direct injection of CO_2 in the deep ocean or enhancement of the biological flux of carbon by fertilization, will likely be dwarfed by the magnitude of the ongoing passive uptake. On the other hand, humanity is already manipulating the terrestrial biosphere on a global scale, and its influence on atmospheric CO_2 is substantial. The effect on the carbon cycle of ecological interventions on land has been mostly inadvertent to date. Most of the interventions have resulted in decreasing the amount of carbon in various terrestrial carbon reservoirs. In particular, woody biomass and active soil organic matter, because of their intermediate turnover times (30 to 100 years), are the largest terrestrial pools affected by land use conversion and agricultural establishment. This past reduction in terrestrial carbon storage, however, suggests the opportunity to increase carbon in terrestrial systems through intentional management. The realization that sequestration of carbon in wood and soil may play a significant role in offsetting CO_2 from fossil fuel burning is already evident in international negotiations.

Concerning how high atmospheric CO_2 might go in the future, two general questions must be answered:

- ***What will be the partitioning of carbon among the mobile reservoirs, and how will climate change affect this partitioning?***
- ***How can the future growth of atmospheric CO_2 be managed?***

Each of these points is examined, and thereafter, a major new research initiative is proposed to address the most compelling scientific issues, an initiative that is also scientifically feasible and cost-effective.

Projecting Future Atmospheric CO_2 Concentrations

The IPCC has provided some scientific basis for international policy decisions by extrapolating the historical behavior of the terrestrial biosphere and ocean into the future. Again, the assumption is that carbon uptake by the terrestrial biosphere will continue to occur through the same mechanisms as at present, and that ocean circulation and biology will remain constant through time (Houghton et al. 1996). However, from coupled atmosphere-ocean simulations with time-dependent radiative forcing (e.g., Haywood et al. 1997), it appears possible that the terrestrial biosphere and ocean carbon cycle might already be experiencing direct effects of climate change today. These effects could become even larger over the next century (e.g., Cao and Woodward 1998, Sarmiento et al. 1998). Further, it seems likely that both terrestrial and oceanic ecosystems will undergo significant indirect responses to climate change and human impacts on the environment, such as NO_x [nitrogen oxides] fertilization, air and water pollution, and CO_2 increase. Such shifts might include changes in species distribution in addition to changes in the supply of nutrients and other ecosystem components that determine carbon cycling.

Terrestrial Ecosystems

Terrestrial ecosystems have played and will continue to play a significant role in the global carbon cycle. Release of CO_2 from land use change has been a significant flux to the atmosphere historically, and could well continue or even accelerate. In addition, there appears to be a significant sink of CO_2 in land ecosystems arising from the synergistic effects of past land use changes, increasing atmospheric CO_2, the deposition of fixed nitrogen, and, possibly, climate changes over the past century or so. To project the consequences of given human activities (such as fossil fuel burning and land use change), it is essential to understand the responses of terrestrial ecosystems. It is likewise important to understand how climate interacts with terrestrial ecosystems. Several factors will control the balance of terrestrial ecosystems with respect to carbon. The current degree of uncertainty regarding all of these factors is high.

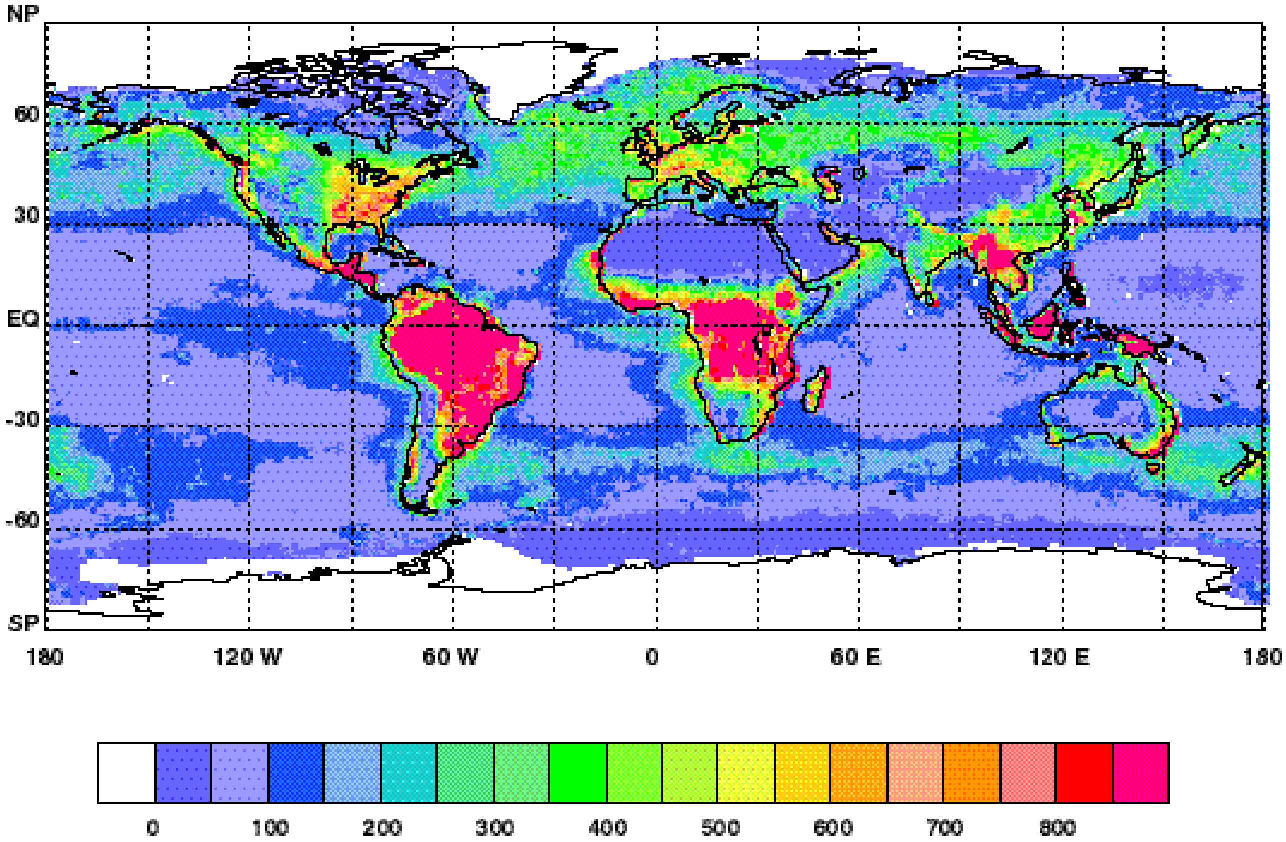
Increasing CO_2 and fixed nitrogen from fossil fuel burning can both act as fertilizers to ecosystems, increasing net primary production (NPP, the amount of carbon processed by photosynthesis in green plants minus that lost through respiration), and possibly carbon storage. Air and water pollution can lead to degradation of the ecosystem and loss of carbon. Observational and manipulative studies have not yet yielded unambiguous results about the magnitudes of these effects, and there are thus substantial disagreements in model predictions.

There is evidence that climate change and variability over the past century may have influenced both the distribution of vegetation and its productivity. The potential exists for significant positive climate feedback in which warming of arctic soils and permafrost, high in organic carbon content, could stimulate the oxidation to CO_2 of much of that carbon (Goulden et al. 1998, Oechel et al. 1993). Most models of vegetation dynamics suggest possible major redistribution of vegetation zones with future climate change. Changes in the extent of ecosystems such as carbon-rich peatlands and forests or carbon-poor deserts could substantially affect carbon storage on land. Although slow changes to long-lived vegetation are difficult to study experimentally, and models of these processes are in early developmental stages, an integrated program of manipulative experiments, paleoecological studies, and continuing observations can facilitate continuing improvements in the models.

Significant integrative research is needed to improve predictive capability for terrestrial ecosystems, both managed and natural. First, the basic science and its representation in models must be improved. Better representation is needed of key processes, such as responses to disturbances, CO_2 warming, nutrient deposition, and atmospheric pollution, including their interactions. Important questions are emerging that require new direct evidence from observational and manipulative studies. Analyses of atmospheric observations also require better models of terrestrial ecosystems. Models are an important tool in inverse analysis of atmospheric data (inverse analysis is a mathematical tool that infers unknown variables from a given set of equations, data and assumptions). Models of the land biosphere are urgently needed for data analysis. Beyond global models, detailed site-specific models are also required to assess the long-term consequences of management options. Such models can be used to appraise the influence of a given forest or agricultural management practice on both commodity production and environmental impacts at the same time, including carbon storage and trace gas exchange. Improving projections of the future carbon balance of terrestrial ecosystems requires an integration of global carbon cycle and climate models (to calculate climate-ecosystem feedbacks on atmospheric CO_2) and management-oriented models for use in decision making about terrestrial ecosystems. Decisions about terrestrial ecosystems will influence—perhaps heavily—the future effects of ecosystems on the atmosphere.

The Ocean

Coupled atmosphere-ocean model simulations (e.g., Haywood et al. 1997) predict a large warming of the surface waters of the ocean (e.g., of 2.5°C by mid next century). They also predict increased stratification of the surface ocean from the higher temperature at low latitudes and increased precipitation in high latitudes. One of the consequences of these changes may be a reduced rate of formation of North Atlantic Deep Water, perhaps as early as the next decade. However, on time scales of a few decades, changes in the rate of convection and vertical mixing appear more important for the surface CO_2 balance than changes in advection. Further, in at least one simulation, ocean CO_2 uptake is particularly impacted by changes



Global, annual net primary production (NPP) (g C/m^2/y) for the land and ocean biosphere. This calculation is from models that use satellite data to calculate the absorption of visible radiation by photosynthetic pigments in plants, algae, and cyanobacteria. The land model (CASA) and the ocean model (VGPM) are similar in their reliance on broadly observed patterns to scale photosynthesis and growth from the individual to the ecosystem level. This calculation, based on ocean data for 1978–1983 and land date for 1982–1990 produces a global NPP of 104.9 Pg C/y (104.9 x 10^{15} g C/y), with approximately half (46.2%) contributed by the oceans and half (53.8%) contributed by the land. These approximately equal contributions to global NPP highlight the role of both land and ocean processes in the global carbon cycle.

in the Southern Ocean compared with other regions of the ocean. These changes in ocean mixing and circulation may reduce cumulative oceanic uptake of CO_2 by 10 to 30 percent between now and the middle of the next century (Matear and Hirst in press, Sarmiento et al. 1998).

Climate change may also have a major impact on ocean biology, which in turn would affect the ocean's uptake of CO_2. One change may be reduced or altered global productivity due to slower upward mixing of nutrients from the thermocline, or increases in productivity associated with anthropogenic nutrients or richer supply of micronutrients by dust transport. Another may be change in taxonomic composition and physiology. Environmental changes that could drive such ecological shifts include warming of surface waters and stabilization of the water column. The supply of micronutrients by dust transport has an important impact on ecology, as in making it possible for nitrogen fixers to exist in nutrient-poor regions (Michaels et al. 1996a). Also important are carbon chemistry changes. The concentration of carbonate ion will decrease by 30 percent and the pH by more than 0.2 in the mixed layer by the middle of the next century. Some changes in taxonomic composition and bulk physiology could have an impact on important carbon cycle parameters. Among these are the ratio of calcium carbonate ($CaCO_3$) to organic carbon production in coral reefs (Smith and Buddemeier 1992) and coccolithophorids, the ratio of organic carbon to nutrients in material exported from the surface, and the amount of carbon locked up as dissolved organic carbon, which presently amounts to about 90 billions of metric tons, or 90 gigatons (Gt C), in the upper 500 meters.

Time-series observations from the past decade show clearly that ocean biota respond dramatically to interannual climate variability such as the El Niño–Southern Oscillation (ENSO) (Karl 1999). Ocean warming due to climate change could lead to changes of comparable magnitude. Simulations with ocean general circulation models show that biological changes may increase the oceanic uptake of CO_2 by 5 to 25 percent, depending on what assumptions are made about how to model the biological response. This effect is large enough to counteract much if not most of the reduction in uptake from mixing and circulation, but the magnitude and even the sign of this effect are highly uncertain.

The relationship between marine ecosystem structure and the rate at which biological processes move carbon between surface and deep waters is an emerging research theme. The most prevalent ecosystem structure of the open sea, particularly in the equatorial and subtropical regions, is one dominated by the microbial loop. The microbial loop consists of very small organisms in a complex trophic structure with efficient nutrient recycling, little accumulation of biomass, and little export of carbon from surface waters to the deep sea (Landry and al.1997). Experimental evidence (e.g., Coale et al.1996) shows that nutrient perturbations to the steady state in these ocean regions leads to enhanced growth and dominance of diatoms and other large phytoplankton. Increased new production associated with diatom blooms, for example, increases carbon dioxide uptake from the atmosphere in surface waters and (eventually) leads to vertical export of particulate carbon to deep waters.

At high latitudes, and particularly in the Southern Ocean, increased stratification in response to climate change may lead to a more efficient biological export of carbon from surface to deep waters, thereby reducing surface nutrients and carbon. The evidence for this effect is based primarily on numerical models (e.g., Sarmiento and Le Quéré 1996) and has not yet been confirmed by direct observation. In subtropical and equatorial waters, however, future warming may cause the opposite effect. Increased stratification of the water column may lead to a reduced supply of either micro- or macronutrients, a shift to N-fixing organisms, and even lower carbon export than occurs today (Falkowski et al.1998). Some evidence implies that such changes are now occurring in the Northern Hemisphere (Karl et al.1997, McGowan et al. 1998). The potential contributions of such changes to the ocean carbon sink are not yet understood. Hypotheses that link warming-induced changes to upper-ocean stratification (and nutrient flux) and changes to marine ecosystem structure and carbon export are testable using long time-series observations. They may also be tested by focused process studies on ecosystem responses to interannual variability (e.g., during warm versus cold years) and other "natural" experiments.

Current understanding of marine ecology and the ability to predict the oceanic response to climate change are extremely rudimentary. It will take at least a decade of research, including long time-series data taken at a number of stations, to significantly improve understanding of the potential responses of oceanic communities to climate change.

Continuing to identify the main hypotheses and goals for the CCSP as in Chapter 2, we can then state another fundamental hypothesis for carbon cycle research:

> Hypothesis 2: The oceanic inventory of anthropogenic CO_2 will continue to increase in response to rising atmospheric CO_2 concentrations, but the rate of increase will be modulated by changes in ocean circulation, biology, and chemistry.

This hypothesis of an increasing long-term ocean carbon inventory (or "the Increasing Ocean Inventory hypothesis") provides a critical focus for concerns about the future long-term effectiveness of CO_2 sinks. One value of a hypothesis concerning future CO_2 sinks is that it challenges us to anticipate when and how it can be tested. The estimation of oceanic CO_2 uptake has been a primary objective of chemical oceanographic programs for more than two decades (GEOSECS, TTO, SAVE, WOCE, JGOFS[1]). Using a variety of direct and tracer measurements, these programs have considerably improved the ability to model the ocean CO_2 sink. The recent advances discussed previously suggest that trends in long-term oceanic CO_2 uptake may soon be susceptible to much more direct verification.

Like the Northern Land Sink hypothesis, the Increasing Ocean Inventory hypothesis cannot be considered in isolation. For example, it explicitly encompasses the need to understand the effects of variations in oceanic circulation, biology, and chemistry. Such variations have been hypothesized to account for the seasonal and interannual variability in oceanic CO_2 exchange associated with the phasing of the El Niño–Southern Oscillation and North Atlantic Oscillation (NAO). Because ENSO and the NAO are also implicated in short-term atmospheric CO_2 variations, they must be considered in the use of atmospheric transport inverse models to constrain the Northern Land Sink. Constraints on the spatial distribution of air-sea fluxes are critical to determining the spatial distribution of terrestrial fluxes. Determining the North American or Eurasian fluxes with confidence requires knowing the North Pacific and North Atlantic fluxes. Thus, the Northern Land Sink and Increasing Ocean Inventory hypotheses are directly related and closely linked in a variety of important ways.

The Northern Land Sink and Increasing Ocean Inventory hypotheses represent a wide array of perspectives that are inherent in carbon-cycle research: not only terrestrial and marine, but also short-term and long-term,

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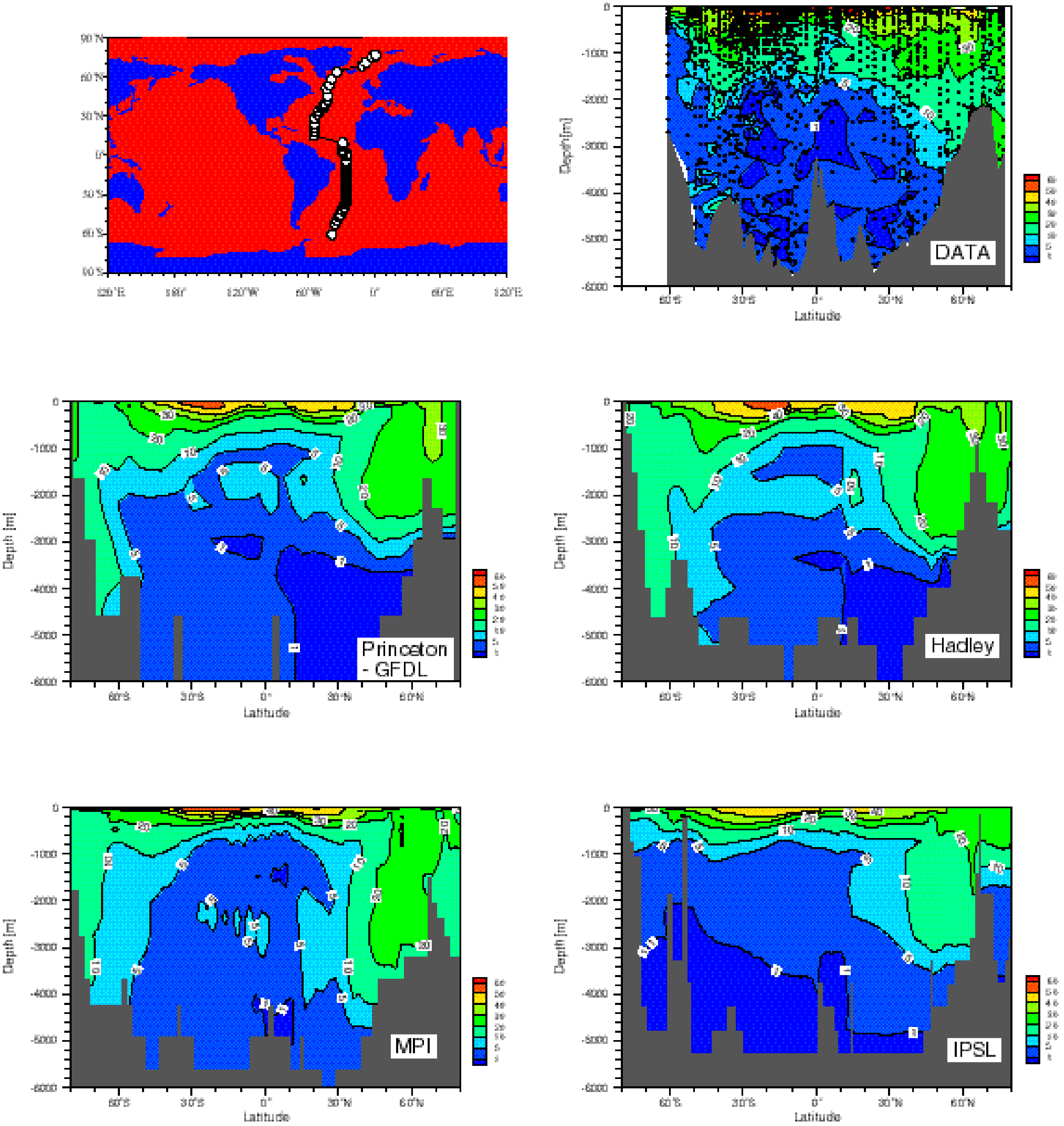
[1] Geochemical Ocean Sections program (GEOSECS); Transient Tracers in the Ocean (TTO); South Atlantic Ventilation Experiment (SAVE); World Ocean Circulation Experiment (WOCE); Joint Global Ocean Flux Study (JGOFS).



Data-based and model estimates of uptake of carbon (mmol/kg) released to the atmosphere by human activities, or "anthropogenic carbon," by the Western Atlantic Ocean along a transect illustrated in top left panel. Most of the anthropogenic carbon in the oceans is found in the upper 1 to 2 kilometers except in regions of deep water formation, such as the North and, to a lesser extent, South Atlantic. The ocean has a large capacity to dissolve anthropogenic carbon, but it takes many centuries to millenia for this capacity to be realized. Predicting the future uptake of anthropogenic carbon by the oceans thus requires models of ocean circulation such as those shwn in the bottom four panels of the figure. These models are able to reproduce the general features of the observed anthropogenic carbon distribution, such as the shallower penetration in the low latitudes, and deeper penetration in higher latitudes. However, there are also many differences among the models, and between the models and the observations. For example, all of the models fail to simulate a sufficiently deep penetration between about 30°N and 50°N, and three of them simulate too much penetration in the South Atlantic.

This figure was constructed by the Ocean Carbon-Cycle Intercomparison Project team (OCMIP) using a variety of data and model sources including: Orr et al. in preparation, Gruber (1998), Sarmiento et al. (1995), Toggweiler et al. (1989), Taylor (1995), Maier-Reimer (1993), Madec and Imbard (1996), and Aumont et al. (1998).

regional and global, spatial and temporal, diagnostic and prognostic. They illustrate the extent of integration that is necessary in a framework of evolving hypotheses concerning the global carbon cycle.

To summarize, predicting the future role of oceanic and terrestrial biospheres in determining atmospheric CO_2 needs to consider the feedback among climate change and terrestrial and marine biogeochemical processes. Climate change will affect the terrestrial biosphere and ocean; and changes in the terrestrial biosphere and ocean will affect atmospheric CO_2. Capturing these mechanisms will require more highly developed models of the terrestrial and oceanic biospheres, ocean mixing and circulation, and their response to warming. A major near-term goal of the CCSP is therefore the following:

> Goal 4: Improve projections of future atmospheric CO_2 concentrations through a combination of manipulative experiments and model development such that appropriate biophysical and ecological mechanisms and carbon cycle–climate feedbacks are incorporated in global climate and carbon cycle models.

Management Strategies

The goal of carbon management strategies is to abate the increase of anthropogenic carbon concentrations in the atmosphere. Two approaches for accomplishing this goal are measures to reduce carbon emissions and measures to increase the uptake of carbon by oceanic and terrestrial biosphere sinks. There are no fundamental physical or chemical barriers to using the energy potentially available in fuels much more effectively to bring down the rate of emissions. Relying on low or non-CO_2 emitting energy sources is another way of reducing atmospheric CO_2 concentrations in the long term. However, in the interim, it is also necessary to consider the option of managing carbon uptake by the oceanic and terrestrial reservoirs.

Exchange with the large geological reservoirs of carbon, such as limestone, is slow. The carbon added to the atmosphere will stay confined to the three "mobile" reservoirs mentioned earlier (i.e., atmosphere, terrestrial biosphere, and ocean) for hundreds of thousands of years. In essence, the burning of coal, oil, and natural gas represents an artificial transfer of carbon from the geological reservoirs to the mobile reservoirs.

The ultimate long-term sink for carbon of the three mobile reservoirs is the ocean. Model calculations show that, on a time scale of 1,000 to 10,000 years, the ocean will absorb about 85 percent of the anthropogenic carbon that has been added to the combined atmosphere-ocean since the beginning of the industrial revolution (e.g., Maier-Reimer and Hasselmann 1987, Sarmiento et al. 1992). The fraction that can dissolve in the ocean decreases as the total amount added to the atmosphere increases. An additional 5 to 10 percent of the combined inventory will be absorbed by the reaction of CO_2 with $CaCO_3$ in sediments on a time scale of 10,000 to 100,000 years (e.g., Archer et al. 1997). One way of managing atmospheric CO_2 is to accelerate the uptake of carbon by the ocean by pumping it into the slowly ventilated deep waters. These calculations assume that surface ocean temperature, salinity, and alkalinity remain constant, and that the marine cycle of CO_2 fixation and sedimentation of organic matter and carbonate skeletons (the "biological pump") does not modify the oceanic carbon distribution significantly.

In the terrestrial biosphere reservoir, photosynthesis removes CO_2 from the atmosphere, but much of the carbon is removed only temporarily (IGBP Terrestrial Carbon Working Group 1998). Approximately 50 percent of the initial uptake of carbon from photosynthesis is lost through plant respiration. Again, the carbon remaining after respiration is net primary production (NPP). Part of NPP is lost as litter and enters the soil, where it decomposes, releasing carbon to the atmosphere. On an annual basis, carbon remaining after decomposition is net ecosystem production (NEP). Further carbon losses occur by such processes as fire, insect consumption, and harvest. These losses yield net biome production (NBP), the critical carbon quantity in considering long-term carbon storage. The IGBP Terrestrial Carbon Working Group (1998) argues that belowground components of ecosystems are especially important because belowground carbon generally has slower turnover rates than aboveground carbon. Slower turnover implies that carbon storage can be maintained over longer periods.

An important outcome of better information on land use change (Goal 3 for the CCSP, as outlined in Chapter 2) will be a stronger scientific basis to analyze strategies for managing global carbon fluxes in compliance with international treaties aimed at increasing terrestrial carbon sequestration. We need to know which management strategies for terrestrial biological processes are cost-effective in forests, grasslands, and croplands. Terrestrial ecosystems are partially constrained by the legacy of land use practices in the past. Land use practices are discontinuous in time and space. Hence, in the case of forests, different stands in the same region will rarely be of the same age class and species composition. They will sequester carbon at different rates and in different amounts in response to a given change in management (e.g., changes in harvest rate or predation control) or climate. Delineating these effects will require close coupling between observed land use patterns and trends and corresponding estimates of carbon flux densities, to create

spatially explicit gradients of carbon flux at regional scales. This effort will require combining satellite and ground-based observation of land use patterns and trends, flux measurements,and process-based modeling. Together, information from all these sources will allow the scientific assessment of management scenarios to increase sequestration of carbon on the land.

The scientific evaluation of management options requires the direct involvement of social scientists in constructing land use histories. Thus,there is a permeable boundary between this science plan and the relevant social sciences. Careful assessments are needed of the social and economic costs and benefits of proposed carbon sequestration policies. One critical element will be the development of credible land use scenarios for the future.

Another important component of carbon management strategies will be the ability to verify commitments. Other sections of this report discuss the estimation of oceanic and terrestrial sinks. An important additional issue is the estimation of fossil fuel emissions. If the global estimate of fossil fuel emissions based on economic accounting methods is off by 10 percent,that would represent an error of 0.65 Gt C/yr—which is more than the reductions envisioned in the Kyoto Protocol. This error is quite large when trying to balance the global carbon budget with oceanic and terrestrial sources and sinks. The financial and economic stakes in correct carbon accounting are of great importance for any country in a world where emissions permits can be traded. Some measurement strategy is needed,independent from statistical and accounting methods,to determine the magnitude of fossil fuel CO_2 emissions on regional and national scales. The only nearly unequivocal (characteristic and stable) tracer for fossil fuel CO_2 in the atmosphere is its complete lack of ^{14}C isotopes.

These considerations lead to another major near-term goal of the CCSP:

Goal 5: Develop a scientific basis to evaluate potential management strategies for enhancing carbon sequestration in the environment and for capture/disposal strategies.

Chapter 4: An Integrated Carbon Cycle Science Program

The previous two chapters of this report summarized our present understanding of the global carbon cycle and the basic questions that confront present-day efforts to better understand it. This chapter presents an integrated plan to achieve the major goals that have been identified:

Near-Term Goals of the U.S. Carbon Cycle Science Plan

Goal 1: Establish accurate estimates of the magnitude of the potential Northern Hemisphere terrestrial carbon sink and the underlying mechanisms that regulate it.

Goal 2: Establish accurate estimates of the oceanic carbon sink and the underlying mechanisms that regulate it.

Goal 3: Establish accurate estimates of the impact of historical and current land use patterns and trends on the evolving carbon budget at local to continental scales.

Goal 4: Improve projections of future atmospheric concentrations of carbon dioxide through a combination of manipulative experiments and model development that incorporates appropriate biophysical and ecological mechanisms and carbon cycle-climate feedbacks into global climate and carbon cycle models.

Goal 5: Develop a scientific basis for evaluating potential management strategies for enhancing carbon sequestration in the environment and for capture/disposal strategies.

These goals are intended to guide research for the period of the next 5 to 10 years.

Two general hypotheses were also identified in Chapters 1 and 2 as those most critical for the U.S. Carbon Cycle Science Plan (CCSP) to address:

Hypothesis 1: There is a large terrestrial sink for anthropogenic CO_2 in the Northern Hemisphere.

Hypothesis 2: The oceanic inventory of anthropogenic CO_2 will continue to increase in response to rising atmospheric CO_2 concentrations, but the rate of increase will be modulated by changes in ocean circulation, biology, and chemistry.

The research program outlined here will ultimately be judged by its ability to provide practical answers to both scientific and societal questions. Scientists and policy makers must be able to evaluate alternative scenarios for future emissions from fossil fuels,effects of human land use,sequestration by carbon sinks,and responses of carbon cycling to potential climate change. Thus,a key motivation for further research is to develop the predictive capability to define responses of the global carbon cycle to change,as reflected in Goals 4 and 5.

Recent assessments of global environmental research have emphasized the need for programs that are both integrated and focused (e.g.,National Research Council 1998). This plan puts forth a program that focuses on key problems, yet maintains breadth to reveal new problems and priorities in those areas where the knowledge needed to define focused strategies is currently lacking. In Chapter 6,this report also proposes a management structure for implementation of the research plan and the development of critical partnerships to ensure continuous reassessment and prioritization of goals.

Much recent progress in knowledge of the carbon cycle has resulted from studies at the global scale for time periods of years to decades. However, to make significant progress in understanding and quantifying the critical mechanisms that will determine future levels of atmospheric CO_2, data must also be obtained for specific geographic regions over a range of time scales. The fingerprints of dominant processes are to be found by studying regional carbon balances and temporal variability. Efforts to address both intermediate spatial scales and longer time scales are thus essential components of the proposed plan.

The program will also study the main processes influencing how carbon cycling may change in the future. These studies will be integrated in a rigorous and comprehensive effort to build and test models of carbon cycle change, evaluate and communicate uncertainties in alternative model simulations,and make these simulations available for public scrutiny and use. Clearly, the systematic incorporation of newly understood mechanisms in models must be accompanied by model integration using high-quality standard inputs and rigorous consistency tests against an array of benchmark data. Data management and data set construction are sometimes underrepresented in hypothesis-oriented programs. This pitfall must be avoided because,ultimately, it weakens the ability to test hypotheses using comprehensive data and to develop powerful generalizations and new hypotheses.

At its most basic level,the global carbon cycle must be viewed as a singular entity. Its various components are so interactive—over so many different scales of time and space—that they cannot conveniently be “isolated”for independent study or modeling. Data are most valuable when combined from a variety of measurements and methods associated with different carbon-cycle components; for example,when oceanic data are applied to help interpret results for the atmosphere and terrestrial biosphere,and vice versa. The present plan,then,proposes three different types of general approach:

- **Extend observations** over the important space and time scales of variability in all active carbon reservoirs
- **Develop manipulative experiments** to probe key mechanisms and their interactions
- **Integrate these data, analysis, and modeling approaches** so that they are mutually supportive and can be focused on key problems.

The observational strategy described in this chapter is designed to combine atmospheric measurements with observations from space, air, land, and sea to reveal specific processes that affect terrestrial and oceanic carbon exchange at regional as well as global scales. While the goal of the terrestrial component of this strategy is ultimately to understand the Northern Hemisphere terrestrial sink, the continent of North America is an excellent focus for the U.S. research community in developing this research objective. North American logistical capabilities are excellent and cost-effective, and there are extensive existing data sets for North American ecosystems, land use, soils,industrial activities, and history. Recent research has pointed to the particular importance of understanding terrestrial carbon exchange in the Northern Hemisphere, and North America’s large geopolitical units facilitate the development of an integrated continental analysis of carbon sources and sinks. Parallel research by European and Asian colleagues will be encouraged to expand the coverage into other parts of the Northern Hemisphere terrestrial biosphere.

Similarly, the northern oceans are relatively accessible, and a solid foundation of oceanic data and knowledge is available to support integration of studies of North American atmospheric CO_2 exchange with studies of CO_2 exchange in the oceanic regions adjacent to it. These foci offer a unique opportunity to combine atmospheric, oceanic,and terrestrial studies in a way that will constrain major components of the global CO_2 budget.

Goal 1: Understanding the Northern Hemisphere Terrestrial Carbon Sink

One principal goal of the CCSP is to establish accurate estimates of the magnitude of the potential Northern Hemisphere terrestrial carbon sink and the biophysical mechanisms that regulate this sink. Several major activities should be conducted in this area:

- An expanded program of atmospheric concentration measurements and modeling improvements in support of inverse calculations and global biogeochemical models
- A network of integrated terrestrial research sites with eddy-covariance flux measurements and associated process studies,manipulation experiments,and models, which as a whole are sufficient to reduce uncertainty about the current and future carbon cycle to acceptable limits.

The two boxes here summarize the specific proposed program elements,which are discussed in detail in the sections that follow.

Goal 1a: Atmospheric Measurements and Models—Major Program Elements and Activities

- Expand current atmospheric monitoring and observational networks to acquire—
  - Vertical concentration profiles in continental source/sink regions
  - Increased continuous measurements (as contrasted with weekly flask data) of CO_2 and associated tracers at selected continental surface stations
  - Flask measurements in undersampled regions, providing the data needed for continental and regional apportionment of net carbon exchange.
- Enhance the suite of measurements at the global network sites to include oxygen, carbon and oxygen isotopes, radon, and other parameters to constrain the locations and processes responsible for the carbon sources and sinks.

Goal 1a (continued)

- Conduct focused field campaigns over North America using aircraft sampling techniques in combination with improved atmospheric transport models and an enhanced flux tower network, to confirm and refine estimates of the magnitude of terrestrial sources and sinks of CO_2.

- Improve inverse models and strengthen connection between models and observations.

Goal 1b: Terrestrial Studies—Major Program Elements and Activities

- Synthesize results of recent and ongoing terrestrial carbon flux studies and use the data to constrain global carbon/terrestrial/atmosphere models.

- Conduct long-term monitoring of changes in above and belowground carbon stocks on forest, agriculture, and range lands using improved biometric inventories that explicitly address carbon issues, along with new types of remote sensing, to determine long-term changes in carbon stocks.

- Develop new technology to facilitate direct long-term flux measurements of CO_2, and install an expanded network of long-term flux measurements emphasizing the acquisition of data for representative ensembles of undisturbed, managed, and disturbed lands along major gradients of soils, land use history, and climate, and with a number of towers and sites sufficient to allow quantification of error in the spatial domain.

- Quantify mechanisms controlling terrestrial sources and sinks, their evolution in the geologically recent past, and the likely course of their evolution over the next decades to centuries. This quantification should be achieved through regionally nested sets of manipulation experiments, other process studies, and CO_2 flux measurements. Measurements should be integrated through a parallel set of nested models, with analyses scaled up to regions through use of regional inventory data.

- Conduct manipulations and focused process studies on ecosystem, local, and regional scales, coordinated with CO_2 flux measurements to quantify the mechanisms controlling terrestrial sources and sinks, their duration, and past and future evolution.

- Develop techniques for monitoring the dynamics of belowground carbon stocks.

Atmospheric Measurements and Modeling for Inverse Calculations

Atmospheric transport of CO_2 integrates the effects of local sources and sinks,with mixing around a latitude circle in a few weeks,and between hemispheres in about a year.A primary test of Northern Land Sink hypotheses requires resolving the longitudinal structure of the surface CO_2 flux,in addition to the variation in latitude. Clearly, the observations will have to define concentration gradients between the continents and the sea and between the planetary boundary layer and the middle and upper troposphere. These are inherently difficult measurements, because atmospheric mixing is so much more rapid around latitude circles than across them,and measurements near sources or sinks are highly variable. Design of the necessary atmospheric sampling program requires careful attention to the spatial and temporal distribution of sampling,the precision of the atmospheric data,and the details of some boundary-layer atmospheric processes that are not well understood at present.

The atmospheric observing system currently consists of roughly 100 sites around the world at which air is collected weekly in paired flasks for trace gas analysis at central laboratories,and few sites where observations are made continuously.The sites are intentionally located in remote marine locations to avoid local "contamination"by industrial or terrestrial emissions or uptake,and are operated at low cost using cooperative arrangements with volunteers. There are very few data acquired at altitude and at mid-continental stations.

To provide meaningful constraints on net terrestrial CO_2 exchange on the regional scale,the observing network will need to be strengthened considerably to characterize spatial and temporal variations associated with the carbon fluxes that need to be measured. The present network is designed to be insensitive to regional net exchanges. A recent evaluation of 10 global tracer transport models used for CO_2 inversions (Denning et al.1999) found that the models converged when compared to the observed values for an inert tracer (SF_6) at flask stations in the remote marine boundary layer. However, they diverged where the data are sparse (aloft and over the continents). This problem is even worse for CO_2 due to the covariance between diurnal and seasonal cycles of CO_2 net exchange and rates of atmospheric mixing,often called the "rectifier effect." Expanding the atmospheric observing network to include routine sampling aloft,particularly over the continents,should be one of the highest priorities for the future. Atmospheric sampling over the terrestrial surface must include vertical profiles through a depth sufficient to capture most of the vertical mixing of the surface signal. At a minimum,this vertical sampling must span the depth of the planetary boundary layer (1 to 3 km in warm sunny weather). A primary research goal should be to determine first the optimal sampling density,

supporting measurements,and combination of continuous versus flask samples, for long-term airborne sampling. Multiple species,such as tracers of industrial activity, and isotopic ratios must also be measured to obtain the information needed to interpret the observations (e.g., Potosnak et al.1999).

The atmospheric boundary layer and the covariance between terrestrial ecosystem processes and near-surface turbulence are not resolved in most of the current generation of global atmospheric models. Most atmospheric tracer transport codes used for CO_2 inversion calculations represent subgrid scale vertical transport very crudely, if at all. Likewise, very few of these models include a diurnal cycle of CO_2 exchange.

However, even if a model could correctly represent the local covariance structure of the fluxes and the turbulence, the influence of the rectifier effect on the observed concentration field at remote flask stations depends on the persistence of the vertical gradient as the air is transported horizontally for hundreds or thousands of kilometers. This process is very poorly resolved in even the most detailed global models, and is not well understood theoretically.

A major effort in understanding the local forcing,spatial scaling,and long-distance transport aspects of the rectifier effect is required,through both observations and models. Testing the Northern Land Sink hypothesis also requires filling the gap at the crucial “middle scale”of the flux-transport-concentration problem. This middle scale between local and large-scale observations is completely missing from the current observing system and models.

The detailed design of the required atmospheric sampling program,which must be coordinated with design of the terrestrial flux network and ocean measurements proposed below, is a major scientific endeavor beyond the scope of this document. However some general requirements are clear. A strategy must be developed for atmospheric sampling over continental regions which takes into account the differences in ecosystem exchanges in stable and convective conditions. This variation must be explored over a range of ecosystems and meteorological regimes by sampling from eddy flux towers,tall towers, balloons,and light aircraft. Continuous long-term measurements of the vertical profile of CO_2 and other trace gases on tall transmission towers allows “representative” conditions to be defined for the planetary boundary layer (PBL) sampling at the local scale (Bakwin et al.1995, Bakwin et al.1998,Hurst et al.1997). Similar information can be obtained from continuous long-term measurements of CO_2 and other trace gases in conjunction with eddy-correlation fluxes defining rates of exchange between the surface layer and the planetary boundary layer (Potosnak et al.1999).Light aircraft can be instrumented with continuous analyzers to determine the boundary-layer budgets of trace gases over areas orders of magnitude larger than the footprint of an eddy flux tower (Desjardins et al.1997, Goulden et al.1998). These types of studies directly address the issues of scalability of tower fluxes,and can be used to design lower cost, routine sampling programs for larger scales.

Independent estimates of regional-scale carbon fluxes by inversion of atmospheric data will require a dense network of samples collected by light aircraft. Light aircraft sampling must be dense enough to capture meaningful gradients in surface fluxes, and must sample both within and above the convective boundary layer. Vertical profiles from light aircraft over a continental region could be coupled with high-altitude transects sampled from appropriately instrumented commercial aircraft (Marenco et al. 1998).

Both inversion calculations and forward models will benefit tremendously from additional constraints such as regionally detailed emissions data and multiple tracers. Samples should be analyzed for CO_2, as well as CO, CH_4, O_2/N_2, and stable isotopic ratios,all of which provide constraints on the carbon cycle. Ancillary data such as PBL structure (from wind profiling and traditional sounding systems),atmospheric transport (from four-dimensional data assimilation systems,4DDA),and the isotopic ratios of other components of the land-atmosphere system (plants, soils,precipitation,and groundwater) are needed. Such a system has been proposed using automated sampling equipment and rental aircraft (Tans et al.1996).

Regional observing and modeling programs have been proposed in other countries on a “campaign”basis,and the results of these studies can provide useful constraints on regional flux estimates using inverse modeling. Regional experiments quantifying carbon fluxes or tracer concentrations are currently underway or planned for the near future in Europe,Siberia,Brazil,and Australia.The design and implementation of U.S.observing systems and modeling programs should be optimized to take advantage of these complementary programs.

Ideally, inverse calculations of the carbon budget should subsume all available information,including flask samples,in situ data,aircraft sampling,air-sea flux measurements and eddy covariance data.Carbon budgets calculated from inverse methods should not, for example,be inconsistent with measured diurnal cycles of CO_2 data collected by regional sampling programs in other parts of the world. The current global observing system is so poorly constrained in the tropics, for example,that tropical fluxes are freely estimated in inversion models as a residual,allowing unacceptable freedom of terrestrial fluxes in higher latitudes without violating global mass balance.Inclusion of new regional data from experiments in Amazonia in these inverse models would provide stronger constraints on the carbon budget of North America, directly addressing uncertainties in the Northern Hemisphere Land Carbon Sink hypothesis.

New approaches to inverse modeling are needed to apply highly resolved atmospheric data to constrain regional fluxes. Atmospheric transport across regional areas is sufficiently rapid that concentration changes will have to be resolved on the order of hours to a few days rather than months or years. Trace gas transport will need to be represented at much higher spatial and temporal resolutions than at present,possibly using "observed" meteorological fields from four-dimensional data assimilation systems,or by incorporating carbon fluxes into models used in operational weather forecasting. Significant improvements in the land-surface parameterizations used in numerical weather prediction would be required.

An objective of the global observational and inverse modeling system should be to provide meaningful integral constraints on spatially extrapolated estimates of carbon fluxes derived by"upscaling"local fluxes using process-based models and remote sensing.These observing and modeling programs,described in the next section, would be extremely valuable in the context of top-down estimates of flux derived independently from the global observing program.

Terrestrial Observations, Experiments, and Models

Studies to refine understanding of terrestrial CO_2 exchange confront fundamental questions. What are the fluxes of carbon into today's ecosystems? Which systems are taking up how much carbon? What factors influence changes in past and contemporary ecosystem carbon storage (e.g.,CO_2 itself, nitrogen deposition,other pollutants, climate,management practices)? How has the rate of carbon storage changed in the past centuries and decades? What systems and management practices cause net losses or gains of carbon? How will fluxes and storage of carbon in the terrestrial biosphere change with changes in climate and the chemical composition of the atmosphere?

Studies of terrestrial carbon cycling must focus on systematic sampling strategies designed to characterize *quantitatively* essential processes and to reject or confirm specific hypotheses concerning responses along gradients of principal controlling factors. There are several current hypotheses concerning the particular ecosystems or processes that take up CO_2 in response to environmental change. For example, variations in temperature and soil moisture (Dai and Fung 1993), growing season length (Myneni et al. 1997), N availability (Holland et al. 1997), CO_2 fertilization (Friedlingstein et al. 1995), and forest regrowth (Turner et al. 1995) have all been suggested to be involved (see, e.g., Goulden et al. 1996, Fan et al. 1998). Although measurements along gradients are a powerful technique for assessing ecosystem responses in systematically different conditions, in practice the factors that determine the changes along the gradient are confounded to some degree. Thus, great care must be used in interpreting observations and experiments along gradients. In addition, the confounding of control variables, together with variability, means that significant replication must be obtained at least at some points along environmental gradients.

The role of land use must be a central subject in any plan for terrestrial carbon research. In the annual terrestrial CO_2 budget summarized above,it is evident that a significant portion of the terrestrial fluxes is related to present and/or past land use. Additional evidence from atmospheric and oceanic measurements suggests that most of the ~1.8 Gt C/yr land sink may be occurring in the Northern Hemisphere (Ciais et al.1995a). Some recent analyses suggest that an appreciable fraction of the total terrestrial sink may reside in North America (Fan et al. 1998,Rayner et al.1998). Inventory information is also accumulating to suggest significant sinks of carbon in North America,although the inventoried sinks are typically smaller than those suggested by the evidence from atmospheric measurements. The vast majority of land in the United States and southern Canada was disturbed in the past and is managed,intensively or extensively for human use. North American carbon sinks,as well as uptake by European or Asian ecosystems,are strongly affected by human activities. Studies of the role of land use history in determining the fluxes are discussed below in this chapter in section "Goal 3: Land Use."

A deliberate sampling and experimental design is required,aimed at characterizing fluxes and processes controlling carbon storage in forests, grasslands, agricultural lands and soils. The design should emphasize not the identification of "typical"sites for a vegetation regime,but the identification of a ***network*** of sites within vegetation types that sample the principal axes of variation. These axes of variation would include not only climate and soils (Schimel et al.1997),but also disturbance type and time since disturbance. A high priority is the development of new methods for measuring carbon fluxes belowground.

A principal focus of studies within this network would be systematic observation of carbon exchange fluxes along environmental gradients. This is now possible to an unprecedented degree. The key gradients (e.g., climate, nutrient deposition, forest age,plant functional types,land use) can be defined. Rates of carbon exchange can be measured. Previous efforts to estimate net CO_2 exchange have been hindered by pervasive small-scale heterogeneity in terrestrial carbon storage,and by difficulties in assessing changes in belowground carbon storage. Forest inventories represent a critical first step in quantifying storage, but they need to be upgraded to provide better information on carbon,coordinated to help scale results from flux stations and airborne regional measurements,and integrated to provide consistent, continental-scale estimates of net carbon exchange. Eddy flux data are providing high resolution on changes in carbon storage on the scale of hectares (e.g., Goulden et al. 1996, Goulden et al. 1998). However, further technological developments are needed to bring down costs and improve the accessibility of the technique and the reliability of the method. (Commercial development of the technology now appears to be underway.) Finally, hectare- to kilometer-scale-resolution data can be extrapolated to regional (and ultimately global) domains using advanced remote-sensing techniques and verified through expanded atmospheric concentration measurements and models described earlier in this chapter.

A network of flux measurements along well-defined environmental gradients provides several valuable products. Fluxes can be directly extrapolated using area weighting from remote-sensing and inventory information. Flux observations can provide information about responses to environmental forcing (such as temperature and soil moisture). Better understanding of the response to environmental forcing can then be used in extrapolations and analysis. Flux measurements allow estimates of carbon sequestration from inventories to be compared to measured carbon uptake. Fluxes can also be extrapolated using models. Estimates of seasonal or interannual variations in fluxes can be compared to changes inferred from atmospheric measurements. Applying this approach to temporal variations is especially important. For example, while interannual variations in local climate and carbon fluxes may suggest hypotheses about large-scale regulation, they provide limited insight without direct large-scale mass-balance constraints. Conversely, estimates of the large-scale atmospheric CO_2 seasonal cycle and sources and sinks provide a vital global constraint on models. However, these estimates provide limited information about the modeled mechanisms and sensitivity without greater spatial resolution and precision in estimated fluxes.

The ability to apply eddy-covariance flux measurements to regions will be limited by knowledge of errors in both temporal and spatial scales. Because the technique accumulates data at high frequency, there is essentially little problem in the temporal resolution of the specific measurements. It is critical, however, that the variability of NEP over seasons and years be captured by continuous, high-quality operation of each of the sites. It is in the spatial domain that problems with regional measures of NEP using the eddy-covariance flux method may arise. A region (or biome) can be thought of as a unit of observation from which samples can be drawn to allow the region to be characterized quantitatively with explicit statements of error for NEP in space. This characterization can be achieved if eddy-covariance measurements are replicated within regions, not only across the axis of a particular gradient (as discussed above) but also normal to the gradient axis in order to quantify variance at each gradient level. The number of replications needed cannot be stated a priority as it is itself a research issue. Nevertheless, adequate replication is absolutely essential to providing information that ultimately can be used to reduce uncertainty in estimates of current and future regional carbon flux and storage. Such replication may depend to a large degree on the development of low-cost, stable, reliable, semiautomated instrument packages that will greatly reduce the manpower and logistical costs associated with the measurements.

The envisioned approach would combine process studies and experiments (designed to increase basic knowledge and improve predictive models) with flux measurements designed to allow models to be tested. A well-designed network of study sites would serve as a focal point for many different types of research. Process studies on nutrient interactions, on feedbacks from species diversity and changes to biogeochemistry, and on climate effects are all needed. Experimental manipulations can help untangle complex mechanisms and test hypotheses for ecosystem responses to conditions outside the current envelope. For example, studies using preindustrial CO_2 levels can yield critical information on carbon storage from past changes. Studies manipulating CO_2, nitrogen deposition, and climate at sites at a range of times since disturbance are crucial for quantifying interactions among these key global change drivers. It is essential that the research network use common approaches and methods with the highest degree of standardization of methods and instruments as possible. Particular attention must be given to quality assurance in the operation of monitoring equipment and conduct of manipulation experiments. Formal protocols will certainly be required at an early stage. Recognizing that new and better methods and instruments will be developed, the networks need to be able to accommodate innovations so that the innovations can be applied across the entire system, not piecemeal.

The United States and other nations already invest significantly in natural resource inventories for management purposes. These inventories should be designed to provide better information on carbon. Only large-scale operational inventories—such as those maintained by government agencies—can provide data from the hundreds to thousands of sites needed for direct spatial integration. The inventory data need to be more effectively integrated with other sources of information, including eddy flux and remote sensing. In addition, it is critical to extend the inventory approach to cover the fate of carbon after it is harvested from forests. This carbon includes not only logging residues, but also manufactured products and waste streams.

Finally, eddy-covariance flux time-series are needed to provide closure on carbon budgets at key sites, to measure CO_2 uptake or loss as a function of the location in the experimental design.

The proposed terrestrial carbon research network poses several significant challenges. For measurements along gradients to have power in rejecting hypotheses or parameterizing models, large sample sizes are required. Today's networks of flux sites number in the tens of installations. Globally this approach will require significantly more measurement sites, an arrangement that requires significant prior investment in autonomous measurement technology and theory to make the technique simpler, more robust, and less expensive. The program must be sustained for a significant period, because the measurements become valuable only when reasonably long time-series have been collected, and they will become more valuable over time.

Clearly, both the design of the initial network and its implementation will also require extraordinary care, statistical rigor, and investment in technology. Enormous resources could be expended on process studies, experiments, flux measurements, and inventories *without* materially reducing uncertainty about either today's CO_2 budget or simulations of future trends. For the nation's scientific resources to be efficiently deployed, an initial synthesis and analysis of existing in situ data (including soil and sediment surveys, forest inventories, and observations at existing Long-Term Ecological Research [LTER] and AmeriFlux sites (LTER maintained by the National Science Foundation and AmeriFlux maintained by the Department of Energy, National Aeronautics and Space Administration, and National Oceanic and Atmospheric Administration), remote sensing, and model results is needed to define patterns of variability. Then, the research community must be engaged in the effort to use this synthesis as a basis for site selection in a network designed to understand patterns at large scales.

Once an analysis of existing data and models is done, a critical set of measurements and experiments can be designed to efficiently sample the space identified. Different sets of measurements may be appropriate for different suites of sites. The design should take advantage of remote observations of land cover and land cover change, which are quite comprehensive for the United States. Similarly, inventory data are already available, and with system and data management upgrades, management data may be made highly useful. With some effort in technology and theory development, the present network of roughly 20 flux measurement sites can be increased by a factor of 2 to 10.

Six other types of studies are proposed to complement the proposed flux measurements at network sites:

1. **Experimental manipulations** of CO_2, temperature, nitrogen, and other key controlling factors. Manipulations are an ongoing line of research that must be enhanced. A number of specific questions about the nature, quantitative importance, and persistence of mechanisms driving the current terrestrial carbon sink can be best addressed through direct experimentation. Manipulations including ecosystem-scale climate change, nitrogen additions, and elevated or decreased CO_2 can provide critical insights on interactions, on responses to conditions in the past or the future, on ecosystem-to-ecosystem variation in responses, and on interactions with other anthropogenic impacts, including harvesting, other land use change, biological invasions, and altered biological diversity.

   The next generation of manipulative experiments designed to understand and quantify the current terrestrial sink should emphasize processes at the ecosystem scale, including responses of both biogeochemistry and ecological dynamics. Studies with preindustrial CO_2 are critical, but will require new technologies, especially for experiments at the ecosystem scale. Experiments to quantify effects of multiple factors, alone and in combination, are also crucial. Currently, we have little idea of the extent to which the carbon sink in forest regrowth includes signals from increasing CO_2, N deposition, or climate change. Similarly, we have no idea of the consequences for carbon storage of vegetation changes, for example, increasing shrub abundance in many of the world's grasslands (Archer et al. 1995). Experiments could be used to probe both the drivers and the consequences of vegetation changes, especially experiments on ecosystems where the transitions can occur quickly.

   The next generation of experiments should also include pilot studies to evaluate deliberate carbon sequestration strategies. Issues concerning the limited spatial and temporal scale of manipulative experiments should receive intensive attention, so that lessons from the experiments can be effectively interpreted and incorporated into global-scale models.

2. **Long-term terrestrial observations.** Expansion and enhancement of the LTER network will pay huge dividends by defining the ecological and current and historical land use factors that regulate sequestration and release of carbon from major ecosystems. The network expansion is envisioned to provide new sites, roughly equal in number to the roughly 20 currently existing, strategically located to examine ecotones, or boundary zones between regions with different vegetations or biomes, likely to play a significant role in regulating global CO_2. Enhancements are needed in two dimensions. Quantitative, ecosystem-level work on carbon stores and turnover should become a major component of each site, and LTERs should become key points for large-scale manipulations and for the expanded flux network. By doubling the budget and number of sites in the current network, and adding important new research tasks, there should be a strong synergy between the carbon focus and present ecological and process-oriented goals of the LTERs, enhancing both.

3. **Intensified flux measurements at sites where detailed process studies are coordinated with eddy-covariance measurements.** Intensive observational studies can be conducted where carbon uptake and many of its controls (N availability, soil moisture, microclimate,light) and mediating variables (Rubisco content of leaves,conductance,stem flow, belowground processes) are measured. In essence,such studies allow natural spatial and temporal variability to perform the experiments that test hypotheses. Hypothesized control processes can be evaluated if a suitable suite of associated measurements (climatic, atmospheric,and biological) is made. These studies share some of the advantages and disadvantages of deliberate manipulations. The major advantage is that the perturbations are "natural," including all time scales. The disadvantage is that the conditions are not under control of the experimenter. This "natural approach" is that followed by the present AmeriFlux network.

4. **Flux scaling studies in which tall towers, boundary layer measurements (Convective boundary layer budgets) and aircraft profiles address the scaling of land surface fluxes to their signatures in the atmosphere.** Opportunistic use should be made of tall transmission towers (e.g.,Bakwin et al. 1995),which allow micrometeorological fluxes to be determined over much larger footprints than typical canopy towers. Additionally, tall towers allow the vertical profile of the eddy flux to be measured,testing scaling strategies by varying the footprint of the measurement. With appropriate inclusion of meteorological data collection (radar wind profilers or balloon sondes),tall towers also allow the direct measurement of the local forcing of the atmospheric CO_2 rectifier effect,which will facilitate larger scale atmospheric modeling. Aircraft observing campaigns should use eddy-covariance sites as anchor points. These programs can be designed to provide flux estimates over a much larger footprint than that of even a tall flux tower, through measurements of continental boundary layer budgets for scales of several tens of kilometers (Chou 1999,Desjardins et al.1997,Lloyd et al.1996) to transects measured by flux aircraft for scales of tens to hundreds of kilometers (ABLE-2/3 experiments, BOREAS,FIFE[2]). These data allow a quantitative evaluation of the relationship among intensive flux measurements,land surface cover, and ancillary process data; and would facilitate the development of scaling strategies by providing spatially extensive snapshots as context.

5. **Remote sensing of terrestrial properties.** Remote sensing must be a critical component of any plan for terrestrial carbon research. Efforts to characterize terrestrial carbon cycling should exploit interaction with programs such as the World Climate Research Program's Global Energy and Water Cycle Experiment Continental Scale International Project (GEWEX/GCIP). This program has already demonstrated success in integrating remotely sensed and in situ measurements of energy and water fluxes. To the extent possible,carbon research plans should be structured so that they can take advantage of improved satellite data products expected in the near future. These products will include new 30-meter Landsat Thematic Mapper-derived land cover data,high-resolution data sets expected in association with the ETA Mesoscale Model, and data products anticipated from the Mission to Planet Earth. Of particular interest is the possible application of advanced algorithms to the upcoming Earth Observing System (EOS) sensors to derive plant canopy functional properties.

6. **Integration of observations with model development.** Understanding terrestrial processes requires that ongoing observations be linked to the continued development and testing of models. It is extremely difficult to develop terrestrial carbon models that include state-of-the-art process representations for all of the needed processes on multiple temporal and spatial scales. Often the limitations of models serve as signposts in formulating and testing new hypotheses. Examples of current model frontiers are the effects of CO_2 on a full suite of plant processes (including allocation of carbon to different parts of a plant), dynamic interactions between carbon and nitrogen budgets, hydrologic changes (such as drying or thawing of boreal peat),and vegetation dynamics such as successional changes over long time scales. Models must also be improved to systematically incorporate information about human and natural disturbance of the land surface. Current models emphasize physiological and biogeochemical processes and largely neglect the carbon storage dynamics induced by cultivation, forest harvest, fire, fire suppression,and other intensive disturbances as well as biological invasions, changes in biological diversity, and other ecological processes

The chief requirement for the progress of modeling—particularly in hypothesis testing—is better integration of models and data. Model development is currently supported by a variety of programs,including NOAA Carbon Modeling Consortium (CMC), Terrestrial Ecology and Global Change program (TECO), Vegetation/Ecosystem Modeling and Analysis project (VEMAP),NSF's Methods and Models for Integrated Assessment (MMIA),and numerous disciplinary programs. Although this diverse range of support encourages innovations,more effort is needed in integration. The assembly of observational data into

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[2] Atmospheric Boundary Layer (ABLE);BOReal Ecosystem-Atmosphere Study (BOREAS); First ISCLIP (International Satellite Land Surface Climatology program) Field Experiment (FIFE)

Photograph of the 447-meter tall WLEF-TV transmitter tower, Park Falls, Wisconsin. The tower is owned by the State of Wisconsin Educational Communications Board, and is being used for measurements of CO_2 mixing ratios (see Bakwin et al., 1998) and atmosphere/surface exchange of CO_2 by eddy covariance. Transmitter towers up to 610 meters tall are located in many areas of the USA.

standard forms that can be used by models is a significant integrative task, without which rigorous testing and comparison of models cannot be achieved. Thus, very different models may appear to have equal "validity," incorrect hypotheses may not be rejected, and the improvement of models and hypotheses may be inhibited. Standard data sets are urgently required for terrestrial model input (climate, soils, disturbance regimes, N deposition) at regional and global scales. Without these standardized inputs, model intercomparisons are meaningless. Standard data sets must be assembled in ways that are compatible with all models simulating particular processes and scales. There is ample precedent for this approach. In meteorology, the production of reanalysis data sets has resulted in long time series of physical variables that are critical in evaluating climate models. These data sets might be valuable as climate inputs to carbon models, but they must be checked for consistency with known carbon-energy-water relationships.

Recent Intergovernmental Panel on Climate Change (IPCC) intercomparisons of global carbon-cycle models were made only after all the models were required to meet consistency criteria based on input of a standard set of historical atmospheric CO_2 and emissions data. Clearly, the systematic incorporation of newly understood mechanisms in terrestrial models must be accompanied by model integration using high-quality standard inputs and rigorous consistency tests against an array of benchmark data.

The implementation of the terrestrial studies described above might proceed as follows:

- An analysis of existing spatial data, model results, and remote-sensing products must be initiated as a basis for an experimental and observing system design that will allow the testing of hypotheses and the extrapolation of site-specific studies. A working group with modest funding should be assembled to undertake this activity. The project should assess the U.S. data, results and products in detail and global information at lower resolution.
- The nation's forest, agricultural, and aquatic monitoring programs should be evaluated with the goal of identifying low-cost/high-leverage enhancements to the existing programs. Collaboration among agency scientists and managers and the broader carbon science community is crucial.
- Flux measurements are an essential part of the program, because they may provide closure on carbon and water budgets, which is difficult with conventional sampling, especially closure on belowground fluxes. However, there are problems with the existing technology and theory. Resources need to be invested to reduce uncertainties in measuring nighttime fluxes, allow use in more complex terrain, and develop cheaper and more autonomous systems. Effort needs to be directed toward developing a rigorous statistical approach to placement of sites for atmospheric monitoring and manipulation experiments.
- A continued effort is needed on modeling, on the integration of new experimental knowledge into models, and on sustained testing of models in increasingly rigorous model-data comparisons. Models are required both for the integration of knowledge about the present, and for prediction of the response of systems to future changes.
- Enhanced manipulative experiments at the ecosystem scale are critical for exploring ecosystem responses to environmental conditions outside the current envelope and for assessing responses to interactions among climate, ecological processes, and anthropogenic changes. Manipulative experiments should be designed to support model development, facilitate scaling in space and time, evaluate proposals for managed carbon sequestration, and enhance broad communication about the role of the terrestrial biosphere in the global carbon cycle.
- Long-term ecological research, with greater emphasis on carbon-related issues, will provide the critical data on ecological and land use historical factors regulating sequestration of carbon.

Goal 2: Understanding the Ocean Carbon Sink

Long-term goals for CO_2 research in the ocean are, first, to quantify the uptake of anthropogenic CO_2 by the ocean, including its interannual variability and spatial distribution; and, second, to understand and model the processes that control the ocean's uptake of CO_2. Uptake of anthropogenic CO_2 can be quantified by measuring either the flux itself or the resulting change in carbon inventory. Both should be carried out, with a strong emphasis on disaggregating the global uptake into contributions from major ocean regions and monitoring temporal variability. The process and modeling goals can be attained by research on the rate-limiting steps for uptake, the causes of spatial and temporal variability, and the better integration of models with data to predict long-term trends. These goals are similar to those for the terrestrial environment, but the major research challenges are distinct. Goals in understanding the ocean carbon sink are the following:

- Develop new technology to facilitate systematic and lower cost long-term observations
- Carry out air-sea carbon flux measurements with a near-term focus on the North Atlantic and North Pacific, to coordinate and integrate results most closely with the terrestrial research on the Northern Hemisphere and tropics

- **Conduct global surveys of oceanic inventories of fossil CO_2 along with relevant tracers,including their evolution with time,in support of inverse calculations and global models of carbon uptake**
- **Realize studies of the physical and biogeochemical processes controlling the air-sea flux of carbon in the oceans,including manipulation experiments and development of models.**

The following bullets summarize the proposed program elements.

Goal 2: Major Program Elements and Activities

a. Required new technology

- Instruments for measurement of CO_2 and related quantities on moorings, drifters, and towed vertical samplers
- Rapid water sampling techniques
- High throughput multi-element analyzers for shipboard carbon system measurements (of dissolved inorganic carbon [DIC], dissolved organic matter, particulate organic matter, alkalinity, temperature, salinity, nutrients, O_2,) and related tracers (CFC's, ^{14}C, ^{13}C, etc).

b. Air-sea carbon fluxes

- Apply new technology to install an expanded network of long-term stations, drifters, and underway measurements, emphasizing acquisition of data for representative ensembles of oceanic regions and conditions, to define by observation the spatial distribution and temporal variability of the air-sea flux.
- Conduct focused field campaigns at basin scale over both the Pacific and Atlantic using aircraft sampling combined with shipboard and ground-based measurements and improved atmospheric transport models. The goal is to confirm and refine estimates of the magnitude of oceanic sources and sinks of CO_2 from pCO_2 (partial pressure of carbon dioxide) data, and to provide the tools and data necessary for improved inverse model estimates of Northern Hemisphere terrestrial sinks.

c. Oceanic inventory measurements

- Synthesize results of recent global ocean carbon surveys in support of global carbon/ocean/atmosphere inverse and predictive model development and planning for future global surveys.
- Initiate ongoing program to repeat global CO_2 and tracer surveys every 10 to15 years to monitor the oceanic CO_2 inventory and its evolution in space and time.

d. Process studies, models, and synthesis

- Vigorously pursue ocean process studies, including manipulative experiments, to improve mechanistic understanding of processes controlling carbon uptake and their sensitivity to climate. This research includes direct measurements of air-sea flux of CO_2, factors regulating biological fluxes, and large-scale tracer release and tracking experiments to define quantitatively the controls on uptake of anthropogenic carbon by the oceans.
- Develop improved models of physical, chemical, and biological processes to analyze process observations and to project how these processes may affect ocean uptake of CO_2 in the future.
- Develop new basin and global ocean carbon cycle predictive and inverse models, including improved process models, to analyze air-sea flux and ocean carbon inventory and tracer observations and to project future ocean uptake of CO_2.
- Develop the use of remote-sensing tools for ocean monitoring of physical and biological properties to gain mechanistic insight and to extrapolate local observations to larger scales.

Until recently, the primary tool used for studying the oceanic uptake of anthropogenic carbon has been models validated with observations of tracers,particularly the distribution of natural and bomb radiocarbon. The absence of carbon measurements to verify model estimates has been a serious limitation in testing our understanding of oceanic uptake. Recent improvements in the precision of measurements of DIC and associated tracers such as O_2 have given us greatly increased confidence in estimating the inventory of anthropogenic carbon directly from DIC. New techniques discussed in Chapter 2 allow filtering out the background DIC concentration and the effects of seasonal and interannual variability. These achievements make it possible to detect the total anthropogenic inventory and its change over time scales on the order of a decade. The measurements are also being used to estimate transport of carbon across sections in ocean basins. Both the tracer-based modeling approach and the inventory method will continue to be important tools in monitoring the oceanic uptake of anthropogenic carbon.

Nevertheless,neither modeling nor the inventory approach can give us the air-sea flux of CO_2 at a given time and place. These methods are thus of limited use in

determining the annual and interannual variability of the carbon cycle, and in constraining inverse models of atmospheric observations. However, such spatial and temporal resolution is required for atmospheric inversions to detect the Northern Land Sink as well as to better understand the processes that control the air-sea flux of carbon and its variation in time. The best way to obtain adequate spatial and temporal resolution is by measuring the air-sea flux. This can be done either directly using techniques that were recently tested successfully for the first time at sea, or indirectly using measurements of ΔpCO_2 multiplied by an estimate of the gas exchange coefficient. The direct technique, though, does not lend itself to the large number of measurements that would be necessary to obtain adequate temporal and spatial resolution. Its primary application will be in the essential task of improving our understanding of air-sea flux processes. The indirect measurement technique is the most promising for obtaining the time-dependent air-sea flux over a given period of time and region of the ocean. The application of the indirect flux measurement technique faces formidable obstacles, as discussed in Chapter 2. However, recent progress in techniques for measuring ΔpCO_2 and in our understanding of gas exchange and ability to study it gives cause for optimism that air-sea flux measurements will contribute significantly to our understanding of the global carbon cycle over the next decade.

In conjunction with measurements of the air-sea flux and ocean carbon inventory, it is essential to study the physical and biogeochemical processes that control the air-sea flux and its spatial and temporal variability. It is not sufficient to know within rough bounds the global rate of carbon uptake. Simulations of climate change show significant warming of the surface low latitudes as well as freshening of the high latitudes. These trends would increase the vertical stratification and have a major impact on ocean circulation. It is very likely that these changes will have a major impact on the transport of carbon from the surface ocean to the abyss, as well as affecting the biological pump. Projections of future trends in atmospheric CO_2 must be based on an adequate understanding of relevant oceanic processes and the incorporation of this understanding into models. Considerable work remains to be done in these areas, building on the promise demonstrated by recent progress.

The identified program elements are discussed in more detail in the following subsections.

Needed New Technology

The processes that control carbon cycling in the ocean exhibit large spatial variance, which itself is not stationary, but changes significantly on diurnal, seasonal, annual, decadal, and even longer time scales. Comprehensive spatial and temporal coverage would be very expensive to obtain with dedicated global measurement programs using current methods. It is very important to assure the development of lower cost, more efficient methods for collecting water samples and making at-sea measurements of the carbon system (dissolved inorganic carbon, dissolved organic matter, particulate organic matter, alkalinity, T, S, nutrients, O_2, and related tracers such as CFC's, ^{14}C, etc). A major need also exists for the continued provision of high-quality DIC standards, which was a major element in the success of the World Ocean Circulation Experiment/Joint Global Ocean Flux Study (WOCE/JGOFS) carbon measurement program. Standards should be developed for other important tracers as well, with particular importance attached to carbon isotopes and nutrients.

Autonomous measurement capability for carbon system parameters is also strongly needed. Time-series measurements are presently limited to locations near island ports such as Bermuda and Hawaii. The present U.S. ocean carbon-cycle time-series stations at Hawaii and Bermuda are run at an annual cost of about $1 million each. Activities supported by the operating budgets include studies of the processes affecting the carbon cycle as well as monitoring of the carbon cycle per se. Significant improvements in the coverage and the economics of the carbon cycle monitoring component of the present activities are possible. The scientific community presently has the technical capability to deploy instruments for measuring the air-sea difference of pCO_2 on commercial and research ships. There has been initial success in deploying reliable instruments on autonomous buoys (Friederich et al. 1995). Further technical developments may allow the addition of in situ monitoring of related variables such as nutrients and oxygen.

A major program of technological development is an essential component of ocean carbon research over the next 5 years.

Air-Sea Carbon Fluxes

We recommend the following programs to characterize the climatological uptake of CO_2 by the oceans, the geographic distribution of uptake of CO_2, and, eventually, its interannual variability.

Time Series Observations. The air-sea flux of CO_2 is extraordinarily variable in space and time due to changes in circulation, temperature, and salinity, as well as biology. The key to determining this flux and understanding its variations is continuous in situ monitoring, including both time-series stations and regular measurements along transects using ships of opportunity.

Temporal variations in some areas, such as the Equatorial Pacific, have been identified as major causes of variability in air-sea CO_2 exchange. Existing time-series studies are located mostly in the subtropical ocean gyres, while there are major gaps in data on regions of active ocean mixing and high biological variability, especially in subpolar and polar latitudes. Temporal variability is greatest in surface and subsurface layers, locations where biological and physical feedbacks are most likely to alter the ocean's ability to absorb CO_2. Characterization and understanding of temporal variance is a prerequisite for understanding the processes that limit rates of ocean CO_2 uptake.

Moored and underway time-series observations should, whenever possible, map a range of properties associated with biological productivity. Extending measurements beyond pCO_2, temperature, and salinity (for example) can give both rate and process information about biological productivity. Concentration measurements of CO_2 and nutrients are valuable in this regard. Precise measurements of O_2 concentrations in the mixed layer, coupled where possible with measurements of inert gas concentrations and wind speed, yield information on net production and ventilation. The measurement of isotopic properties gives rate information of interest: the $\delta^{13}C$ of CO_2 constrains net production (Zhang and Quay 1997), while the triple isotope measurement of dissolved O_2 constrains gross production (Luz et al. 1999). Measurements of atmospheric O_2 concentration give valuable information about instantaneous and annually averaged ocean carbon fluxes. Ongoing flask sampling can reflect interannual variability and long-term trends in ocean carbon fluxes. Continuous concentration measurements, now becoming possible, should be developed and used for more detailed studies.

Focused Field Campaigns. An important lesson of carbon cycle research has been how much knowledge of one carbon cycle component depends on knowledge of others. One of the major constraints on the magnitude of the terrestrial sink and its spatial distribution has been knowledge of the air-sea carbon flux and its spatial distribution. In particular, addressing the Northern Land Sink hypothesis will require focused field campaigns over both the North Atlantic and North Pacific to estimate the air-sea flux of carbon during the time terrestrial fluxes are analyzed. These campaigns should include aircraft sampling as well as shipboard and autonomous measurements, and will require improved atmospheric transport models for analysis.

Future field campaigns should focus on areas of critical importance to our understanding of the global carbon cycle. In particular, the Southern Ocean air-sea flux is presently poorly constrained and its temporal variability is unknown.

Oceanic Inventory Measurements

We recommend two programs to characterize the oceanic inventory of fossil CO_2 and its evolution over time:

Thorough analysis of recent ocean carbon observations. At present, the most robust constraint on ocean uptake of CO_2 comes from surveys and time-series of carbon system measurements carried out with instruments and methods now available and analyzed by techniques like those discussed in Chapter 2. Essential complementary measurements include those of carbon isotopes, the standard hydrographic and nutrient measurements, and transient tracers of ocean circulation. These surveys and time-series measurements provide direct in situ constraints on ocean CO_2 uptake that additionally provide strong constraints on the role of the terrestrial biosphere in the global carbon budget.

Over the past decade, the WOCE/JGOFS programs have provided an invaluable baseline on the current state of the ocean that will be useful for assessing future changes. Unquestionably, however, survey and time-series measurements must continue beyond the WOCE/JGOFS era to answer fundamental questions, such as whether oceanic CO_2 uptake is increasing or decreasing globally in the future. Such work is the analogue of the current network of atmospheric measurements, but substantially more difficult to implement. To plan the best possible program of continuing ocean observations, needed spatial resolutions must be determined, along with which variables to measure at what accuracy. A high priority over the next few years must be to use the current vastly increased oceanic data set to answer these questions and to design an optimal survey program.

Monitoring the evolving fossil CO_2 inventory in the oceans along with related tracers. Monitoring the evolving fossil CO_2 inventory is an essential long-term component of any effort to understand oceanic CO_2 exchange. Because the costs of conducting comprehensive surveys are presently very high, we propose that the needed measurements be accomplished through a reduced-level but continuous effort rather than the global "snapshot" paradigm of previous expeditions. This activity would be an ongoing and focused on specific limited areas each year. The goal would be to cover the entire world every 10 to 15 years. This approach would cost less per year and would assure maintenance of the required measurement expertise and capability for the long term. The ongoing survey could exploit strong linkages with other efforts such as CLIVAR (Climate Variability and Predictability programme) and GCOS (Global Climate Observing System) to make efficient use of ship time. It is thus critical to ensure that tracers relevant to the carbon cycle (e.g., DIC, O_2, temperature, salinity) are covered in programs like CLIVAR that have the goal to monitor temporal trends in ocean properties.

The measurement suite should include total alkalinity and should frequently include a third CO_2-system property such as pH to assure internal consistency. The measurement of ^{13}C and TOC [total organic carbon] are essential, as are the development and use of standards. Measurements should include transient tracers, which provide temporal information about ocean mixing and water mass history that is essential to interpreting fossil CO_2 distributions. Finally, they should include bioactive chemicals such as iron whose oceanic distribution is poorly known but is likely an important influence on ocean carbon fluxes.

A complementary approach exploits the fact that the invasion of anthropogenic CO_2 into the ocean looks, in aggregate, like a vertical transport problem that can be effectively attacked through studies of the distribution of transient tracers. Various tracers are now available to span a variety of mixing scales ($^{3}H/^{3}He$, ^{14}C, CFC-12, SF_6, HFCs). Some of these tracers reveal mixing over the critical longer (decadal and century) time scales; and some help identify current short-term invasion rates for comparison with older data. Large-scale tracer release experiments provide an independent means to assess vertical transport rates and mechanisms. Likewise, direct eddy flux measurements are just starting to become available to test parameterizations of air-sea exchange.

Process Studies, Models, and Synthesis

We recommend the following four programs:

Selected studies of processes that control the mechanisms and rates of air-sea CO_2 exchange, vertical transport within the seas, and cycling of DIC and alkalinity. Ocean process studies yield understanding of the basic mechanisms controlling the ocean carbon cycle. Process submodels are also required in models of the time-dependent air-sea flux. Ideally, process studies and observational systems should be linked as intimately as possible to help determine the response of ocean carbon fluxes to interannual variability in climate forcing, and to identify feedback mechanisms. Some important processes that need to be studied are gas exchange and the physical processes that determine the rate of anthropogenic carbon transport from the mixed layer into the thermocline and deep ocean. Also important is the role of biological processes in determining the spatial and temporal variability of air-sea fluxes and anthropogenic carbon uptake. A major issue is the sensitivity of physical transport and biological processes to ocean properties that are likely to change with climate change. Knowledge of seasonal and interannual variability as well as direct manipulation experiments will be an important source of information. A deeper understanding of what controls the biological pump in the ocean is required, including the role of micronutrients such as iron and zinc, whose input to the ocean may be affected by climate, land use, or pollution. Program oversight must assure that priority is given to studies that can make a genuine contribution to understanding future atmospheric CO_2 levels.

One challenge is characterizing marine ecosystems well enough to model their effects quantitatively on air-sea carbon fluxes. Process studies include direct manipulation of the environment, such as the large-scale iron enrichment studies (Coale et al. 1996), as well as systematic observations of the effects of "natural experiments," such as El Niño. Process studies, and in particular ecosystem-level manipulations (along the lines of the recent iron fertilization studies) should be used to evaluate the host of biological mechanisms proposed as potential feedbacks on ocean carbon uptake (Denman et al. 1996). Possible feedbacks that can be tested include modifications of iron fertilization rates of HNLC (high-nutrient, low-chlorophyll) regions, particularly in the Southern Ocean; subtropical nitrogen fixation rates; Redfield carbon to nutrient ratios of export material; community allocation of sinking versus suspended/dissolved material; calcification rates; and subsurface remineralization depth scales. The effects of coastal eutrophication and elevated UV radiation have also been hypothesized as significant, but are rather poorly constrained.

An emerging research theme is the relationship between ecosystem structure and the export flux of carbon. Ecosystems dominated by the microbial loop recycle carbon efficiently and show very little export of carbon, whereas other regions dominated by diatoms and other large phytoplankton tend to show a large carbon export. It is important to understand how changes in ocean stratification and circulation in response to changes in climate will affect the ecosystem structure and uptake of anthropogenic carbon.

Improved process models. Mathematical models are required to express the relationships between physical forcing and biogeochemical processes, to evaluate the implications of results and observations for upper ocean pCO_2 variations and ocean carbon uptake. Seasonally resolved models of the circulation and physical properties of the upper ocean will improve the ability to take into account the influence of temperature, salinity, and transport on sea surface pCO_2. To consider interannual and longer term variability, as well as the effects of climate change, is essential to explore how changes in sea surface temperature, ocean circulation, stratification, and sea ice formation all affect the atmosphere-ocean balance of carbon. Biological models embedded into models of physical circulation will help further explain the large role that seasonally and interannually forced biological processes play in regulating upper ocean chemistry and CO_2 partial pressure in the mixed layer. Models with sufficient resolution to simulate meso-scale processes will be needed to study interactions that determine many of the ecosystem processes. A close collaboration with physical oceanographers studying ocean variability is an essential component of this program.

Improved basin and global carbon cycle models. A new generation of models must be developed for long-term projections of carbon uptake, integrated with the observations to allow data to be assimilated and to test the models. Conversely, models must be able to simulate the distribution of important quantities that can be tested in the field and must otherwise help in designing field experiments. For example, because variability in ocean hydrographic structure and ocean carbon cycling is in most instances associated with circulation changes, variations of carbon and hydrographic parameters will be correlated. An analysis that does not account for this covariance can be seriously in error, and a model that does not simulate the observed covariance will be wrong. Such problems will require a synthesis activity involving both model simulations and measurements. Program structures must be implemented to force both modelers and experimenters to make this integration happen.

Remote-sensing observations and numerical models are a natural marriage inasmuch as ocean in situ observations are often too sparse to initiate or validate model fields. Satellite data are often better matched to the time and space scales of models, but satellites generally measure only very simple indices of biological and physical processes and distributions. Thus, models are necessary to extrapolate simple satellite indices to more complex biological and physical processes and distributions consistent with the accuracy provided by in situ measurements and as required for carbon cycle research.

Remote sensing of ocean conditions and processes. Remote sensing is an important tool for extrapolating measurements and calculations in time and space and for providing estimates of key environmental parameter values needed by coupled physical and biogeochemical ocean models. Remote-sensing observations can also provide critical information during process studies and large-scale manipulation experiments.

One important application of satellite data is to relate the CO_2 transfer velocity across the air-sea interface to “sea surface roughness” on ocean-basin scales. Accumulated evidence suggests that estimates of wind velocity alone are not sufficient to estimate transfer velocity, owing to other factors that also influence surface roughness. These factors include the sea surface wave spectrum and resulting surface renewal and near-surface turbulence (Jähne et al. 1987), which are affected by surfactants (Frew 1997) as well as wind forcing. In particular, small-scale waves (small gravity and capillary waves) are believed to play a primary role in promoting gas exchange, and some of the scattering properties of these waves are observable with space radar sensors (scatterometers and altimeters). One focus for future efforts should be understanding the relationship between radar backscatter from small-scale surface waves and the transfer velocity. This work will require the complementary use of satellite altimeter and scatterometer data to increase spatial and temporal coverage, as well as in situ studies to develop appropriate equations relating transfer velocity and surface roughness. An essential complement to satellite estimates of net carbon fluxes comes from atmospheric O_2/N_2 data. These provide a fundamental constraint on seasonal new production (that portion of primary production that does not represent internal mixed-layer recycling) on a hemispheric or basin scale, and the interannual variability in these rates.

Current estimates of mean ocean primary production must be improved at basin to global spatial scales and daily to interannual temporal scales. Satellite-derived fields of near-surface phytoplankton chlorophyll concentrations are essential to developing the calculations and models needed to do this (Behrenfeld and Falkowski 1997). An essential focus of this work should be the assessment of new production. New production is more closely related to the net flux of CO_2 from surface to deep waters than is total primary production. The relationship between new production and net primary production is not a simple proportionality. Estimating new production requires knowledge of nutrient budgets of surface water, as well as net primary production. Direct measurement of nutrient concentrations is not possible from space, but sometimes concentrations of major plant nutrients such as nitrate can be related by regression to sea surface temperature on regional scales (e.g., Kamykowski and Zentara 1986). Mineral aerosols are one of the primary sources of iron and other trace elements that limit new production and net primary production in some important ocean regions, including the Southern Ocean. Aerosol plumes and sea surface temperatures are both detectable by space sensors. It may therefore be possible to use satellite data to help quantify nutrient budgets in the upper ocean, and hence rates of new production.

Advanced ocean color sensors will help improve estimates of global primary production. For example, the satellite MODIS (Moderate Resolution Imaging Spectrometer) and MERIS (Medium Resolution Imaging Spectrometer) will provide estimates of chlorophyll fluorescence, which can then be used to estimate phytoplankton quantum efficiency or at least the phytoplankton photoadaptive state. The additional spectral bands and higher signal to noise ratio of these advanced sensors will also provide some capability to distinguish phytoplankton functional groups and thus some capability to classify ocean ecosystem structure on large scales.

Several advanced ocean color sensors are planned by NASA and other international space agencies for the next five years, but plans are very uncertain for the post-2005 timeframe. By the end of the next decade, basic ocean color measurement capability may be transferred to operational satellites (e.g., the NOAA/DOD/NASA National Polar-Orbiting Operational Environmental Satellite System, NPOESS,project), but it is not clear if the full capabilities anticipated from MODIS and MERIS will continue beyond the middle of the next decade. Cooperation and coordination among international space agencies should be encouraged to ensure the continuing remote-sensing capabilities required to support future carbon research programs.

Goal 3: Assessing the Role of Land Use

Chapter 2,in its final section,discussed the importance of land use to the overall carbon cycle,as well as to understanding the time history and spatial distribution of carbon sources and sinks. Goal 3 of the CCSP is therefore to establish accurate estimates of the impacts of historical and current land use patterns and trends on the evolving carbon budget at local to continental scales. The following are the major program elements and activities proposed to move toward this goal.

Goal 3: Major Program Elements and Activities

- Document the history of agricultural expansion and abandonment and its impact on the contemporary carbon balance of North America. Conduct intensive historical land use analyses across environmental gradients, in coordination with the proposed North American network of eddy flux measurement sites.
- Improve observational capabilities in tropical regions through cooperation with tropical nations, including international expeditions and exchanges and training of scientists and managers.
- Apply the observational programs discussed under Goal 1 in the tropics, including long-term observations and modeling.
- Couple socioeconomic analysis of land management strategies with biogeochemical models to evaluate the social and biophysical viability of future carbon sequestration options.

The emphasis of the proposed program elements and activities is the tropics and North America. As discussed in the final section of Chapter 2,the tropics are important because of the magnitude of the postulated deforestation source in this region. The focus on North America complements the proposed terrestrial sink program element by providing information on the history of the observation sites.

The data needed to construct reliable land use histories have temporal and spatial gaps over large parts of the world. In the tropics particularly, the expansion of cropland, much of it unrecorded,is presumed to be a major contributor to deforestation (FAO 1995). The unrecorded tropical cropland expansion tends to be highly fragmented,making its monitoring by remote sensing difficult with all but the highest resolution sensors. Afforestation in the Northern Hemisphere mid-latitudes is a significant component of the Northern Land Sink, yet there is a lack of uniformity in the criteria used to enumerate afforested area and define associated carbon flux densities (Nilsson and Schopfhauser 1995). A major effort is needed to assemble land use histories for both tropical deforestation and Northern Hemisphere afforestation. The basis for such histories includes a variety of potential data sources (e.g.,national censuses,provincial and local land use surveys and tax rolls, remotely sensed imagery, and proxy measures such as changes in local population and technology regimes). These land use histories must be spatially explicit (of county-level or finer resolution, depending on data availability) and should extend as far back in time as needed to capture the current impacts of past disturbances on carbon fluxes in a particular region.

A wide range of historical data have been applied to the estimation of CO_2 emissions from land use (e.g., Houghton et al.1983,Melillo et al.1988, Foster 1993). Recent progress has focused on the merging of many kinds of historical records with satellite-derived measures of land cover, and on the use of increasingly sophisticated models of ecosystem response (e.g., Foster 1995). This approach constrains historical reconstructions to be consistent with the geographic distribution of current land cover, and provides the spatial resolution needed to test hypothesized sources and sinks. As high-resolution atmospheric sampling continues and expands in the future, records of CO_2 and its stable isotopes,combined with records of ^{14}C,CH_4, and other indicators of particular land use effects (e.g., N_2O),will become increasingly valuable as historical constraints.

Of particular concern in reconstructing historical emissions is the question of a pre-agricultural steady state. Although ice core records indicate that the global CO_2 budget was near a steady state for thousands of years before the 19th century, this evidence does not assure that particular regions were not net sources or sinks for carbon. For example,several studies have suggested that high-latitude soils were still sequestering carbon as part of their recovery from the most recent deglaciation (Billings et al. 1982,Harden et al. 1992). Estimates of human emissions typically assume a pre-agricultural steady state (e.g., Houghton 1993), whereas direct assessments of CO_2 fluxes may reflect local non-steady-state effects. Thus,integration of emissions estimates and flux observations must include cautious consideration of steady-state assumptions.

Estimates of human CO_2 emissions must account for CO_2 fluxes associated with materials removed to locations other than the sites of original growth or burial. The need to account for the fate of forest products is widely recognized (Houghton et al.1983). However, confusion persists about what oxidation of products from previous harvests should be reported in accounting for the net effects of forestry activities (Houghton 1993). Recently, Stallard (1998) has suggested that eroded soil carbon constitutes another "off-site" form of carbon that must be explicitly included in carbon budgets. Because agricultural activities are known to have vastly increased historical rates of erosion in northern temperate latitudes,the fate of eroded carbon is directly relevant to testing the Northern Land Sink hypothesis.

Goal 4: Improving Projections of Future Atmospheric CO_2

Better projections and information are needed to meet future societal needs:

Goal 4: Major Program Elements and Activities

- Improve representation of physical and biological processes in models of the carbon cycle to reflect observations and new knowledge more accurately.
- Provide a framework for rigorous analysis of observation and independent comparisons and evaluations of climate and carbon models using comprehensive data and both formal and informal model assessment activities.
- Develop new generations of terrestrial biosphere and ocean carbon exchange models, including the roles of both natural and anthropogenic disturbances, succession, and the feedbacks through climate change and anthropogenic perturbations to carbon dioxide and nutrients.
- Develop coupled earth system models incorporating terrestrial and oceanic biogeochemical processes in climate models of the atmosphere and ocean.
- Predictions the future evolution of CO_2 concentrations, for use in evaluating the consequences of societal decisions.

The foundation for predicting future changes in the carbon cycle is understanding the mechanisms that regulate it,the way those mechanisms respond to environmental changes,and the ways those mechanisms interact. Like current understanding,advances in the future will be based on a combination of observations,manipulative experiments,and synthesis via models. Useful models will range from qualitative conceptual models to schemes for connecting or extrapolating observations,to simulations of multifactor processes. Models based on all these approaches can provide powerful tools for asking "what-if" questions about the consequences of future events. Manipulative experiments can provide a mechanism for direct tests of critical model predictions at a range of spatial and temporal scales.

Models

The following provides an overview of the types of models and experiments needed for prediction,including the necessary scientific foundations for credibility.

Models for Data Analysis. A vast array of observations of the natural carbon cycle and results from experiments that manipulate controlling variables will emerge from the proposed program. Models designed for data assimilation and analysis represent a critical step in developing more refined experiments.Inverse and diagnostic models (the latter used to probe data sets) are the bridge between the data collection,conceptual understanding, and predictive models. For example,tracer transport models use atmospheric observations to test rates of transport derived from general circulation models (GCMs) or assimilated meteorological fields. Inverse models use atmospheric and oceanic observations of concentrations to estimate surface fluxes,providing a test for hypotheses about the time-space variability of fluxes.Inverse modeling thus forms a link between data,theory, and prediction,providing constraints on today's fluxes that should be consistent in models of the potential future.

Advanced Component Models and Scaling. Process and theoretical studies lead to new understanding and,in turn,improvement in model output,as mechanisms are incorporated into models. The impact of processes on the whole system must be evaluated by comparing the improved models to earlier formulations and to observations,and by conducting sensitivity analyses to determine their importance.

Some new scientific results must be scaled in time and space. For example, the rectifier effect (again, the covariance between diurnal and seasonal cycles of CO_2 net exchange and rates of atmospheric mixing) can be understood by micrometeorological and plant physiological theory. However, as it occurs on finer spatial and temporal scales than those resolved in global models, an approach for aggregating the effects of the rectifier has to be developed. Similarly, the biochemical effects of CO_2 on photosynthesis have been understood for over a decade, but the impact on long-lived, whole plants, plant communities, and ecosystems is unclear. To achieve the objectives listed for Goal, 4 a vigorous program linking process studies to modeling must be maintained for the new science to be incorporated in local and global predictive models.

Models for Decision Analysis. The great majority of terrestrial systems are currently managed. Management choices have implications for carbon storage (e.g., choices such as no-till agriculture, fire suppression, length of forest harvest rotation, and fertilization). Carbon storage is one factor to consider in making land management decisions, and reliable tools are needed for evaluating the carbon storage consequences of various land management scenarios. There is an urgent need for local- or regional-scale models in agriculture, forestry, urban ecosystems, and marine systems that can be used to evaluate the effects of specific interventions (e.g., no-till agriculture, deep ocean CO_2 injection) to enhance carbon storage, along with assessing associated environmental and economic consequences. These models will form a link between the basic science of the carbon research community and the needs of stakeholders and decision makers.

Carbon System Models and Carbon-Climate Models. The carbon system is intimately coupled to the physical climate system. Indeed, the focus on carbon derives from the role of CO_2 as a greenhouse gas. To project the large-scale consequences of changes to the carbon cycle, it is necessary to link knowledge of the carbon system to that of the climate system. For example, if enhanced concentrations of greenhouse gases disrupted oceanic circulation, the ocean carbon system could be affected by changes in both physics and biology. These changes would help shape the effect of any anthropogenic increase in CO_2 emissions on atmospheric concentrations, thus modulating the climate response.

Similarly, feedbacks could occur through terrestrial systems, with terrestrial carbon exchange possibly modified by climate then affecting atmospheric CO_2, in turn modifying the climate impact of any given anthropogenic emission scenario. These feedbacks are presently uncertain, depending on the rate, magnitude, and spatial distribution of climatic changes. For example, if climate changes are greatest in peatlands at high latitudes, CO_2 emissions would likely increase. More equable warming could result in either increases or decreases of carbon storage in the terrestrial biosphere.

To analyze the potential effects of future industrial and land use emission scenarios, Earth system models are required that couple physical models of the atmosphere, ocean, and cryosphere to biogeochemical models of terrestrial and marine ecosystems. Earth system models predict partitioning of emissions of CO_2 (and other greenhouse gases) between the mobile terrestrial, oceanic, and atmospheric reservoirs, and then predict climatic response and the effects on biophysical processes in the land and ocean.

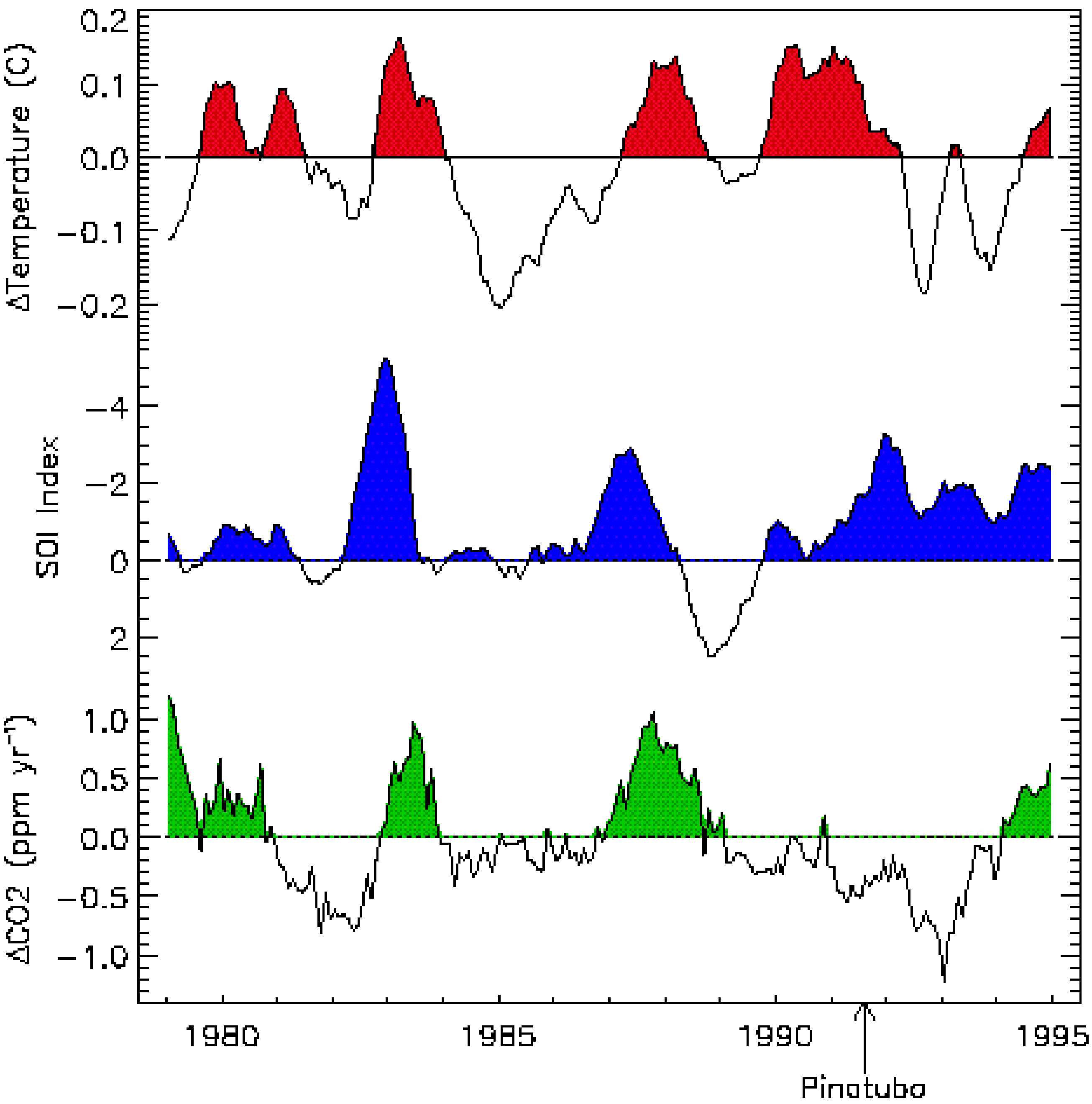
Earth system models build on the knowledge of mechanisms gained in process studies and advanced component modeling studies, and on the evaluation of knowledge derived from diagnostic studies and historical and paleorecords. They will allow us to examine questions about the relationships among policy choices, sources and sinks, and resulting concentrations. These models demand rigorous examination of knowledge, extensive computing resources, and sustained efforts of testing and refining using integrated knowledge from the Carbon Cycle Science Program overall.

All of the above models must be painstakingly compared to observations, requiring strong commitment to testing and refining models. It can be very difficult to test large-scale models against real data sets, obtained in specific locations and at specific times. A coordinated effort to promote rigorous comparisons of models and measurements is needed on the part of the agencies involved in the CCSP.

Experiments

Experimental studies on the future of the terrestrial carbon cycle should be used to probe controlling processes, especially when the nature of the controls may be obscured by spurious correlations or long time constants. These studies should explore the behavior of key mechanisms to forcing outside the range of current ambient conditions, and evaluate responses to forcing from simultaneous changes in multiple environmental and ecological factors. In addition, well-designed experiments can be powerful tools for making results from carbon cycle research accessible to a broad range of stakeholders. Manipulative experiments are, however, complements to models, not full alternatives. The processes controlling the future terrestrial carbon cycle operate over a broad range of spatial and temporal scales. Many processes with the potential to dominate future changes in terrestrial carbon storage—for example, changes in the tree species that dominate forests or changes in the frequency of wildfire—are beyond access through short-term, small-scale experiments. Even if it were feasible to make an aggressive commitment of resources to work at greater temporal and spatial scales, manipulative experiments lose their utility as the time scale of the experiment merges into the tempo of global changes, the far from fully replicatable grand experiment at the global scale.

Manipulative experiments can provide powerful access to key uncertainties about the future trajectory of the global carbon cycle. However, many aspects of the terrestrial carbon cycle are very difficult to study with manipulative experiments. Consequently, the research targets need to be selected with careful attention to the likely importance of the focal processes, the efficiency with



Interannual variations in temperature, the Southern Oscillation Index (SOI) (which correlates with El Niño cycles), and the growth rate of CO_2. Recent work has suggested that observed variations in the growth rate of atmospheric CO_2 may bear the signature of climate effects on ecosystems and the oceans. Understanding the mechanisms that have caused global terrestrial and ocean carbon exchange to vary over the period of observation provides a vital test for the "scaling" of process level knowledge and a basis for predictive modeling.

which the experiments probe these processes,and the feasibility of obtaining the critical information using other approaches. In addition, experiments must be designed for effective integration with observational studies and models. The following approaches should be pursued and enhanced.

Natural Experiments. Frequently, nature presents a ready-made experiment,providing investigators an opportunity to study ecosystem responses to a major environmental forcing. Natural experiments are often permanent or at least persistent features of the landscape,allowing unique access to responses with long time constants,usually with little or no cost for maintaining the natural manipulation. Recent studies with ecosystems near natural CO_2 vents are a good example of the applicability of these features for understanding the future of the global carbon cycle (Raschi et al.1997). The Hawaiian lava flows with a range of different ages and local climates represent a parallel example for basic ecological research that is fundamentally relevant to the carbon cycle (Chadwick et al. 1999,Torn et al.1997).

Natural experiments are invaluable links between long-term observations and purposeful manipulations. They are natural system analogs of research designed to take advantage of recent patterns of land use change. Because these experiments provide unique opportunities to observe long-term,and sometimes large-scale, responses to controlling factors,they should receive greater emphasis. Natural experiments that should be evaluated include not only CO_2 vents and gradients of substrate age,but also steep,topographic gradients of temperature and precipitation, geothermal features,and sites with unusual flora and fauna as a result of isolation. Natural experiments form a continuum with gradient studies. Some of the most powerful uses of the natural experiment approach may lie in combining common gradients with much less common natural experiments.

Multifactor Manipulations. Results from global change experiments are often difficult to interpret in more general terms. Ecosystems targeted by different experiments typically differ in a number of features,creating a barrier to partitioning control for the different responses among the different features. Multifactor manipulations can play a critical role in enhancing the foundation for generalization and reducing uncertainties about future responses. The next generation of multifactor experiments should address two kinds of questions. First,how do ecosystem-scale responses to global change components change when the global changes occur in combination? Experiments should consider interactions among elevated CO_2, warming,and altered levels of precipitation,nitrogen deposition,and ozone. Second,how do the characteristics of ecosystems themselves affect response to global change? A new generation of experiments should focus explicitly on the way that differences in ecosystem characteristics influence responses to global changes. For example,matched manipulations on substrates of different age or with ecosystems of different biological diversity can greatly enhance the ability to generalize. Some of these experiments should focus on the interface between land use and atmospheric change,with manipulations of CO_2, temperature,and other environmental factors at sites of different ages since disturbance, with different management practices,and with different levels of anthropogenically stimulated biological invasion. Multifactor experiments should address a broad range of mechanisms that may influence future carbon storage. These mechanisms range from direct responses of plant growth,to enhanced success of one or more plant or microbial species,to altered decomposition,to changes in sensitivity to fire,pests,or pathogens. Integrating results from these multifactor experiments in models and general interpretations will present many challenges,but it is much wiser to confront the challenges than to ignore the processes to which these experiments provide unique access.

Experiments with Model Ecosystems. The agenda of multifactor experiments is challenging,complex,and essential. Many of the processes that may play critical roles in ecosystem responses have large spatial scales and long response times. This circumstance places a high priority on optimizing the trade-offs between experimental tractability and relevance to the ecosystems with the largest potential impact on the carbon cycle. As in many fields of science,progress can be rapid if a sizeable fraction of the resources is invested in studies on experimental models. These are systems chosen with an emphasis on tractability and access to the key processes,and with much less emphasis on the model system's quantitative contribution to the global carbon cycle. For example, studies on annual grasslands can address multiple global change factors while allowing reasonable replication and large numbers of individuals per replicate. For other purposes,studies on artificial ecosystems in meso-cosm facilities may provide a useful balance of tractability and relevance. With sufficient resources and planning,useful experiments on model systems might operate on a large scale,addressing, for example,the relative success of grassland species and rapidly growing trees under a range of manipulations.

A research program with an emphasis on model systems will require careful planning and coordination across experiments. Scaling interpretations from the models to the systems with the most direct relevance to the carbon cycle may require experiments deliberately designed to address uncertainties in the scaling. In the longer term, we should expect a continuing iteration among experiments, observations, and models. Evidence from one of these approaches will receive added value from extension across

the others, and hypotheses suggested by one approach will be tested by evidence from all three approaches.

Goal 5: Evaluating Management Strategies

Goal 5: Major Program Elements and Activities

- Synthesize results of global terrestrial carbon surveys, flux measurements, and other relevant results, and use this analysis to develop the scientific basis for management strategies to enhance carbon sequestration.
- Determine the feasibility, environmental impacts, stability, and effective time scale for capture and disposal of industrial CO_2 in the deep ocean and in geological reservoirs.
- Define potential strategies for maximizing carbon storage that simultaneously enhance economic and resource values in forests, soils, agriculture, and water resources.
- Identify the criteria to evaluate the vulnerability and stability of sequestration sites to climate change and other perturbations.
- Document the potential sustainability, lifetimes, and interannual/decadal variability of different managed sequestration strategies.
- Provide estimates of the uncertainties related to managed sequestration that are required for policy discussions and decisions.
- Develop the monitoring techniques and strategy to verify the efficacy and sustainability of carbon sequestration programs.
- Create a consistent database of environmental, economic, and social performance measures for the production, exploitation, and fate of wood and soil carbon "from cradle to grave" (for wood, from stand establishment through final disposal; for soil carbon, from formation through burial).
- Develop and parameterize an analytic framework for predicting and evaluating management and policy alternatives considering material transfer, economics, societal factors, wastes and emissions, raw material, labor and energy inputs, carbon sources, sinks, and fluxes, and output for mass carbon balance.

Human land use may be directed toward enhancing terrestrial carbon sinks through a variety of management options. Focusing on the United States, such options include manipulation of forestry practices (such as harvest dynamics, and pest and pathogen control) and agricultural land management practices (such as tillage, crop rotations, and fertilizer use; see Lal et al. 1998). To evaluate the potential of management strategies to sequester carbon, there must be improved process understanding of the relationships between changes in land cover and biophysical controls of carbon exchange. One way to gain such understanding is the close coupling of historical information on land use with eddy-correlation experiments across a network of sites encompassing large temporal and spatial variability of fluxes and land uses (beginning with the AmeriFlux network). The land use information is needed to infer historical ecologies (e.g., species composition, soil organic matter dynamics) that help explain current carbon fluxes. Where possible in this network, experimental designs should allow for the observation of the effects of alternative management strategies (e.g., fire suppression, age-selective forest harvesting). Efforts should be made to ensure that new tower sites have highly variable land use histories. This will broaden the base of knowledge from which to project future fluxes. Further coupling of land use and carbon flux information with biogeochemical models, such as those participating in the Vegetation/Ecosystem Modeling and Analysis project (VEMAP), may be used to predict carbon uptake by whole ecosystems.

Results from the U.S. Forest Service Forest Inventory Analysis (FIA; Schroeder et al. 1997), of periodic measurements of wood volume on thousands of plots of land classed as "forest," indicate lower values of net carbon accumulation in forests (about 0.3 Gt C/yr) for North America than are inferred from inverse analyses (0.9 to 1 Gt C/yr) or tower flux data (~0.7 Gt C/yr). However, the FIA data set has not been optimized nor sufficiently analyzed as yet to ensure that the estimated rates for net carbon sequestration derived from it are accurate. The focus has been to define the wood volume potentially available for harvest. Thus, wood volumes on land reclassified as nonforest and wood harvested as forest products are both removed from the inventory, but a very large quantity of this wood may remain in the form of wood for long periods. Properly accounting for such "removals" in the carbon budget should increase corresponding estimates of net carbon sequestration by 50 to 100 percent. In the CCSP, we propose broadening the FIA to incorporate an explicit focus on carbon, including upgrading the sampling scheme, increasing the number of parameters measured, and increasing the frequency of measurements.

In deep ocean sequestration of CO_2, industrial CO_2 recovered from fossil fuel power plants may be injected directly into the deep ocean for disposal. This arrange-

ment would circumvent the slow natural transfer rate of CO_2 from the surface to the deep ocean. Laboratory studies and in situ experiments show that liquid CO_2 is denser than seawater at water depths below about 3,000 meters. Additionally, rapid growth of CO_2 hydrate crystals along the water-liquid CO_2 interface has been observed. Thus, liquid CO_2, when piped onto the seafloor, is likely to settle there and be quickly transformed into solid hydrate forms. The liquid CO_2 and the hydrate crystals dissolve gradually into the overlying seawater and mix into the surrounding deep sea. The retention time of CO_2 in the deep ocean depends on ocean transport and chemical processes such as neutralization reactions with calcareous sediments. Once the water returns to the ocean surface, some CO_2 can escape back to the atmosphere. Hence, disposal in relatively isolated regions of the ocean is preferred because of longer retention times. The effects of acidified seawaters on benthic ecosystems must be evaluated before any large-scale disposal can be contemplated. Near-field as well as far-field distributions of CO_2 around a disposal site must be investigated. The scientific investigations outlined in the CCSP, such improvements in ocean general circulation models (GCMs), will be directly applicable in evaluating CO_2 sequestration in the oceans.

Not all management strategies will be economically viable or socially acceptable. For example, over the long run, a rising global demand for timber products may provide a strong inducement to keep forest harvest cycles shorter than the optimal time for sequestering the greatest amount of carbon. Collaboration among biogeochemical modelers, and economists and other social scientists will be necessary to examine the economic efficiency and social desirability of various management strategies. Such collaboration will require information flows across a permeable boundary between the initiatives proposed in this plan and associated work in the human dimensions research community.

Observing and Discovering

An essential complementary perspective to testing defined hypotheses is suggested by the second central scientific question for the CCSP: "What will be the future atmospheric CO_2 loading resulting from both past and future emissions?" It is very difficult to frame this question within the context of a single hypothesis or even a framework of closely linked hypotheses. Scientists must look toward the future with considerable humility, bearing in mind the significant uncertainties involved in identifying the processes responsible for a carbon sink as large as the hypothesized Northern Land Sink, or in trying to predict how the ocean sink may develop over time. Some issues concerning future carbon cycling can be addressed through such hypotheses as the Increasing Ocean Inventory. It is also possible to formulate alternative assumptions as competing hypotheses for carbon cycling in the future, but none stands out as pervasively important or useful in the sense that the Northern Land Sink and Increasing Ocean Inventory hypotheses dominate current studies. Questions about future atmospheric CO_2 levels highlight the need for a comprehensive and balanced program of observations, manipulative experiments, and models. These must contribute to the focused testing of hypotheses while remaining comprehensive enough to entrain the new ideas and discoveries that will guide hypotheses for the future. Through testing current hypotheses, unforeseen questions, as well as answers, will surely emerge.

In particular, current attempts to project the future require assumptions and speculation that extend well beyond the range of issues of any program focused on presently testable hypotheses. A future could be hypothesized for atmospheric CO_2 based on reasonable emissions scenarios, consistent with the notion that future trends will follow the pattern of past trends (in biological and ocean uptake, emissions, etc.). However, this assumption encompasses many untested hypotheses. For example, the IPCC scenarios for future CO_2 levels are based on models that have been calibrated using a "fertilization effect" to account for the past and present "missing" carbon sink. Yet this effect is just one of many proposed mechanisms for terrestrial carbon uptake, and large-scale efforts to test it are just beginning. It is unknown how stable terrestrial uptake mechanisms are; the fertilization effect might be expected to continue for much longer than some other contributing mechanisms, such as reforestation in the United States and Europe. Likewise, the IPCC CO_2 scenarios depend on ocean models that assume a steady climate. These assumptions seem increasingly precarious as more is learned about the interplay between oceanic and atmospheric dynamics, and as the prospect of significant changes in the global climate system become more likely. Clearly, even as the scientific community works toward resolving uncertainties through focused hypothesis testing, strong action is necessary to assure that new ideas and discoveries continue to help solve questions about the future behavior of the Earth system.

As this report has made clear, an essential component of the research strategy is a sustained observational effort. This endeavor should provide improved, quantitative estimates of natural and anthropogenic carbon distributions, sources, and sinks, and their temporal and spatial variability at regional as well as global scales. Efforts to develop more focused studies of particular problems, or tests of particular hypotheses, should not obscure the need to continue and expand a program of comprehensive basic observations, with parallel modeling to assimilate the data. Because these observations will be useful in assessing carbon sequestration activities, policy needs must be treated with utmost attention during planning. The design and implementation of such a program,in a cost-effective manner and in concert with the international research community, is a major task.

In addition to a program of comprehensive observations,support is suggested for four types of studies outside the realm of programs to test current hypotheses. Because all these study types are inherently innovative, they are defined by example here, rather than by descriptions that might prove too restrictive.

Studies That May Anticipate "Surprises." Some studies may help reveal unexpected interactions between the global carbon cycle and the climate system. Recent studies of paleoclimate have revealed the past occurrence of surprising short-term instabilities in the Earth's climate system. Concerns about instabilities in future climate must be extended to the potential effects of these instabilities on carbon cycling.

An example of one such surprise was the finding of coupled atmosphere-ocean simulations of climate change, which predict large increases in the vertical stratification of the ocean with warming in lower latitudes and freshening in higher latitudes. These changes would lead to large reductions in ocean thermohaline circulation as well as in vertical mixing in general (Manabe and Stouffer 1994). The impact of these changes on ocean biology would likely be extremely large. The effects on the air-sea balance of carbon are difficult to predict,,because of the counteracting effects of slowed circulation and a potentially more efficient biological pump taking up a higher fraction of surface nutrients (Sarmiento et al.1998).

Climatic warming appears to promote carbon storage in mid-latitude forests,but possibly to promote release of much larger stores of organic carbon from boreal forests and peatlands through increased rates of fire and mineralization (Goulden et al.1998,Kasischke et al.1995)

Studies That Suggest Innovative Hypotheses or Ideas. Creative ideas often do not fit preconceived hypotheses or priorities. Important new concepts may arise from unexpected sources,often from scientific subdisciplines not normally associated with carbon research.

A recent paper (Stallard 1998) uses evidence from geomorphology and sedimentology to hypothesize that large amounts of carbon may be buried on land as a result of enhanced erosion and subsequent deposition accompanied by fertilization associated with cultivation. This study has focused attention on the need to account for the fate of large quantities of eroded soil carbon.

The hypothesis that iron might play an important role in oceanic photosynthesis has a long history. However, the first trustworthy in vitro tests of the hypothesis had to await the development of accurate techniques for measurements in seawater (Martin 1991). Recent in situ iron fertilization experiments provide dramatic support (Coale et al.1996) for the bottle experiments. It has been hypothesized that iron supply played an important role in the changes of atmospheric CO_2 content of the last ice ages (Martin 1990). Iron also also appears to be a major factor in nitrogen fixation in the low-latitude surface ocean (e.g.,Karl et al.1997,Michaels et al.1996a,Michaels et al.1996b). A major source of iron to the ocean is dust delivered through the atmosphere. One notable question that has arisen,then,is whether changes in dust transport that accompany climate change could affect oceanic photosynthesis.

Studies of Past Geologic Variations in the Carbon Cycle. It is widely recognized that the global carbon cycle has varied in the geologic past. Analyses of gases sampled from ice cores have shown that atmospheric CO_2 and CH_4 concentrations varied in concert with the pronounced fluctuations between glacial and interglacial climatic conditions over the past several hundred thousand years (Barnola et al.1987,Stauffer et al.1988, Jouzel et al. 1993). Larger past CO_2 variations—comparable to those anticipated from future human activities—have been inferred from models based on the geologic record of the last 100 million years and longer (Berner 1994). Many of the processes involved in these changes are so slow that they have little relevance to time scales of usual human concern. However, the geologic record is a vital source of information about the dynamic nature of carbon cycling and its interactions with the global climate system over a broad spectrum of time scales. Geologic research can provide important and unexpected insights that are directly relevant to the principal questions addressed in this science plan.

Measurements from the paleorecord suggest that exchanges between reservoirs of the carbon system are not static on millennial time scales. For example,analyses of an ice core from Taylor Dome,Antarctica,show that atmospheric CO_2 concentrations changed over time during the Holocene,with a steady increase from 260-280 ppm over a period of 7000 years (Indermühle et al.1999). These changes may have been due to changes in the amount of terrestrial biomass and/or ocean CO_2 storage. Numerical models of anthropogenic CO_2 generally assume that a steady state existed before human influence. This assumption appears to be reasonable for global models because the rate of CO_2 change during the Holocene was very slow compared to the anthropogenic CO_2 perturbation. However, the changes indicated by the ice core data may be quite significant for studies of carbon budgets on a regional scale,because the inferred imbalances in the carbon cycle are not likely to have been uniformly distributed over the Earth's surface.

Using precise correlations among ice and sediment cores,paleoclimatologists have shown that the most recent glacial cycles were punctuated by large and extremely abrupt climate events (of years to decades)

(Blunier et al.1998,Dansgaard et al.1993). Many of these rapid events appear to correlate with abrupt changes in atmospheric methane (Brook et al.1993,Chappellaz et al. 1993),and some may have been associated with modest changes in atmospheric CO_2 (Stauffer et al.1998). Thus, even on time scales of years to decades,there is geologic evidence of close interaction between climate and the carbon cycle. The evidence suggests that atmospheric methane may be a more sensitive indicator of certain changes than atmospheric CO_2.

Studies of the "Human Dimensions" of Future Carbon Cycle Trends. Future terrestrial carbon budgets will be strongly influenced by human land use. The best attempts to forecast future trends may be confounded by uncertainties about future human activities that are influenced by factors beyond the usual scope of scientific interests in carbon cycling.

Future rates of tropical deforestation will depend largely on the expansion of regional agricultural capacity. Most of the developed countries,which are usually outside the tropics,will depend almost exclusively on technology-driven increases in productivity per unit land area to increase future capacity. In these countries,new changes in the amount of cropland in production are likely to be negligible.The developing countries will depend on a mix of increases in productivity along with expansion of cropland to increase future capacity. Excluding China,these countries have about 2.5 billion hectares of land on which rain-fed crops could give reasonable yields,with approximately 80 percent of it in tropical Africa and Latin America (FAO 1995). Much of the deforestation taking place in the tropics is the result of the disorderly, unrecorded expansion of cropland (FAO 1995). The FAO (1995) projects that deforestation from this unrecorded expansion of cropland will not only likely continue,but will probably do so at a rate exceeding that required to meet national agricultural capacity targets. Quantification of rates of unrecorded conversion of tropical forest to cropland is a critical need for projecting future rates of deforestation.

Expected Results

The ultimate goal of the U.S.CCSP is to provide the scientific understanding required to predict future concentrations of atmospheric CO_2 and evaluate alternative scenarios for future emissions from fossil fuels,effects of human land use,sequestration by carbon sinks,and responses of carbon cycling to possible climate change.

These issues are addressed by Goals 4 and 5—improving projections of atmospheric CO_2 through complementary methodologies and by incorporating regulating mechanisms,and developing a scientific basis for carbon sequestration management strategies. Achieving these two goals will permit us to carry out several critical tasks:

- Present a new generation of models, rigorously tested using time-dependent,three-dimensional data sets,suitable for predicting future changes in atmospheric CO_2.
- Develop management and mitigation strategies that optimize carbon sequestration opportunities using terrestrial ecosystems,primarily forest and agricultural systems,in addition to evaluating the efficiency of ocean carbon sequestration.

Currently, estimates of terrestrial sequestration and oceanic uptake of CO_2 vary significantly, depending on the data used and the analytical approach (e.g., Forest Inventory Analysis,direct flux measurements in major ecosystems,inverse model analysis of CO_2 data from surface stations, changes over time of global CO_2, O_2, $^{13}CO_2/^{12}CO_2$, etc).

The proposed research program under Goals 1,2,and 3,will reconcile these estimates to a precision sufficient for policy decisions by providing new types of data and new, stringent tests for models and assessments. The specific deliverables from these three goals are as following.

Goal 1 is to establish accurate estimates of the magnitude of the potential Northern Hemisphere terrestrial carbon sink and the underlying mechanisms that regulate it.

- Define the existence and magnitude of past and present terrestrial carbon sinks.
- Elucidate the impacts of climate variations (e.g.,length of growing season,soil moisture,long-term temperature changes),of fertilization (CO_2, NO_x, etc.),and of land use changes on atmospheric CO_2.
- Document and constrain uncertainties related to the potential Northern Hemisphere terrestrial carbon sink.

Goal 2 is to establish accurate estimates of the oceanic carbon sink and the underlying mechanisms that regulate it. In the near-term,the focus will be on the North Atlantic and North Pacific oceans to best complement the terrestrial focus on the Northern Hemisphere and tropics.

- Incorporate better understanding of ocean processes in currently undersampled regions,such as the Southern Ocean,into general circulation models (GCMs).
- Determine the existence,magnitude, and interannual variability of oceanic carbon sinks and sources on a regional scale through assimilation of new observations.
- Explain observed changes in the ocean carbon sink due to variations in circulation and biological and chemical changes using enhanced models tested rigorously against new observations.
- Incorporate improved oceanic CO_2 flux estimates to improve constraints on inverse models for estimating

terrestrial sinks.

Goal 3 is to establish accurate estimates of the impacts of historical and current land use patterns and trends on the evolving carbon budget at local to continental scales.

- **Document the existence,location,and magnitude of carbon sources and sinks resulting from historical and current land use changes and land management practices in critical regions.**
- **Provide improved assessments of the uncertainties related to land use,particularly for agriculture in North America and the tropics.**

The results of all the studies under goals 1 through 5 will be communicated to the public and policy makers in papers published in peer-reviewed journals.

Chapter 5: Summary of Program Elements and Resource Requirements

Table 5.1 breaks out the Carbon Cycle Science Plan (CCSP) program elements and summarizes the research components and approximate costs. The elements are also mapped onto the CCSP goals as described below.

Initial Funding Priorities

Most of the program elements outlined below serve more than one of the major long-term and five-year goals. Again, the program requires a coordinated, integrated approach by the responsible agencies: the value of an integrated program will greatly exceed the return from uncoordinated program elements.

The individual program elements described in this plan, however, are not at equal stages of readiness. Some program elements represent work that has been constrained by limited resources in the past and could begin immediately with a near-term infusion of funding. New technology enterprises, for example, have suffered disproportionately in the recent past due to such resource constraints. Since many of the program elements in the CCSP call for focused technology development prior to large-scale implementation, we recommend that a high priority be placed on funding those technology development efforts that have been deferred due to insufficient funding. More specifically, the following program elements should be considered as high priorities for initial funding:

- Both facility and technology development for the enhanced flux network, airborne sampling, and automated and streamlined ocean sampling for long time-series and underway measurements
- Airborne CO_2 monitoring programs, both dispersed weekly measurements and in support of regional studies
- An expanded and enhanced surface monitoring network for atmospheric CO_2
- Improved forest inventories (with carbon measurements a key focus and an explicit goal) and development of new techniques for remote sensing of above-ground biomass
- Analysis of World Ocean Circulation Experiment/Joint Global Ocean Flux Study (WOCE/JGOFS) data for CO_2 uptake by the oceans
- New ongoing program of air-sea carbon flux and ocean inventory measurements
- Continued ocean process studies and enhanced manipulation experiments
- Enhanced development of Earth system modeling to include interactive carbon and climate dynamics.

Mapping of Program Elements to CCSP Goals

The following paragraphs map the program elements shown in Table 5.1 to the goals and objectives of the Carbon Cycle Science Plan.

Goal 1: Program Elements 1-4, 6-9, 11

The program elements (1) expanded terrestrial flux network, (2) airborne CO_2 observation program, (3) global CO_2 monitoring network, and (4) land use inventories, taken together, address the first part of the CCSP Goal 1: to quantify the Northern Hemisphere terrestrial sink and more generally, to quantify the global terrestrial sink for CO_2. Program elements (1), (2), and (3) together provide direct long-term measurements defining sources and sinks on regional scales. The proposed airborne observations (2) are capable of providing integrated measures of regional net exchange several times per month; the conceptual framework for interpreting these observations needs to be strengthened and tested through a series of strategically planned regional observation experiments (6). The expanded flux network (1) complements the other elements by determining monthly and annually averaged regional net uptake or release in typical ecosystems. The flux network will be able to define the systematic differences between flight days and non-flight days for the airborne profile measurements. Flux data can help account for CO_2 net exchange on days when analysis of the regional net exchange is not possible from atmospheric data, e.g., during frontal passages or large weather events.

Improved carbon and land use inventories (4) provide a first-order check on the inferences from atmospheric measurements. By telling us where the carbon is going (or coming from), program element 4 also contributes significantly to the second part of Goal 1, to understand the underlying mechanisms that regulate the Northern Hemisphere terrestrial sink, and more generally, global terrestrial sinks and sources. The long-term terrestrial observations (7), process studies and manipulations (8) provide

Program Elements and Resource Requirements*

The following table breaks out the program elements and summarizes the research components and approximate costs. In Chapter 5, these elements are mapped onto the program goals that were outlined above. Both program goals and program elements are discussed in greater detail in Chapter 4 and Chapter 6.

Project Element	Deliverable	Description	Development/Start-up	Operations Cost
1. Expanded Flux Network[†]	Net CO_2 exchange across major biophysical gradients	100-150 eddy flux network sites, operated long-term	Technology dev-. ($5M) and initial installation, ($15M) over 5 yrs	$20M/yr
2. Airborne CO_2 Observation Program[†]	Three-dimensional and temporal distributions of CO_2 and tracers over North America, analyzed to define regional sources/sinks, and constrain atmospheric transport models	Newly developed weekly monitoring network at 50 distributed North American sites deployed on general aviation aircraft with a combination of flask and on-board continuous sampling units; development and operation supported by periodic intensive field measurements (element 6 below)	$10M	$10M/yr
3. Global CO_2 Monitoring Network	Enhanced space/time data for CO_2 and tracers, defining regional sources/sinks on a global scale, and constraining atmospheric transport models	Increased number (by a factor of 3) of flask and continuous monitoring stations measuring CO_2 and tracers, emphasizing continental and remote marine locations; vertical profiles at selected locations as specified in element 2.		$10M/yr
4. Global Terrestrial Carbon and Land Use Inventories	Vegetation cover, above-and below-ground carbon, and rates of change; input data, constraints, and representation of mechanisms in biogeochemical models	(a) Expanded and reformed Forest Inventory Analysis program to include carbon as a focus, with shorter return intervals, more ecological measurements and greater transparency and traceability (b) New satellite observations (nested high-resolution and LANDSAT imagery, new radar mapping) (c) Analysis of current soil carbon inventories and expansion to monitor eroded carbon and other effects of land use on soil carbon	(b) $10-30M/yr for 5 yr (c) $5M	(a) $10M/yr (b) $10M/yr (c) $5M/yr
5. Reconstruction of Historical CO_2 Emissions	Estimates of historical sources and sinks due to human land use, to be used to constrain predictive models.	Analysis of existing data, synthesis into data sets available for carbon modeling, and development of new historical carbon-cycle models; significant role for remote sensing (LANDSAT 7, MODIS)	$2M	$2M/yr
6. Regional Observational Experiments	Direct regional determinations of fluxes and concentrations of CO_2, greenhouse gases, pollutants	Coordinated airborne, ship, terrestrial, and satellite experiments integrated with model development and testing (e.g. BOREAS)		$5-10M/yr
7. Long-Term Terrestrial Observations	Long-term vegetation, soil, and flux data for major biomes, new emphasis on disturbed and managed sites	30-40 long-term regional sites to evaluate natural disturbance and management effects on carbon fluxes (e.g. increasing focus on carbon, and greater number and types of sites in the NSF LTER network)		$40M/yr
8. Terrestrial Process Studies and Manipulations	Long-term, large-scale effects on the biosphere and on carbon sequestration of predicted environmental changes not occurring in nature today	20-30 major, long-term experiments at ecosystem scale manipulating CO_2, nutrients, water, ozone, temperature, etc.	$20-30M	$20-30M/yr
9. Global Ocean Measurements (surveys, time series, remote sensing)	Ocean/atmosphere fluxes; basin-scale net uptake of anthropogenic CO_2 at reduced cost, and interpretation of seasonal variances, atmosphere-ocean-biology interactions.	(a) Complete analysis of recent global survey data (b) Develop and deploy time-series and drifting buoys and automated towed vertical samplers for CO_2 and related parameters (DIC, DOM,POM, alkalinity, O_2, nutrients, $^{13}CO_2$, $^{14}CO_2$, T, S) and tracers of ocean circulation (CFCs, ^{14}C, $^3H/^3He$), reduce cost per measurement, increase data flow	$25M	$30-50M/yr
10. Ocean Process Studies and Manipulations	Define effects of biology, circulation, atmospheric deposition, and river fluxes on the distribution of oceanic carbon, and rates of invasion/release of industrial CO_2	(a) Physical and biological studies of dispersion of anthropogenic CO_2 and controls on new production/uptake (b) Ocean manipulation experiments (~2/yr duration) to examine hypotheses such as the role of iron in ecosystem production		(a) $10M/yr (b) $10M/yr
11. Modeling and Synthesis	Develop and apply models for analysis of data, synthesis, prediction, policy	Improved ocean, atmosphere and land simulations, rigorous, independent, comparisons of models with data. Develop Earth System models that predict CO_2 and climate interactively		$15-30M/yr
TOTALS	**Present new knowledge, meet societal needs, devise cost-effective approaches**	(Note: estimated current annual spending for carbon-focused work in FY1998 was $40-50M)	$135-300M over 5 years	$200-250M/yr

*For explanation of acronyms, see the acronym list at the end of this report.

[†] Technology development will be a critical focus in the initial phase of this activity.

fundamental tools to develop new understanding of terrestrial sinks and sources.

Estimates of the Northern Hemisphere terrestrial carbon sink made from atmospheric CO_2 observations are very sensitive to the magnitude of the carbon sink in the North Atlantic and North Pacific. Oceanic observations (10) in the North Atlantic and Pacific Oceans thus provide important constraints on the Northern Hemisphere terrestrial carbon sink.

Modeling and synthesis (11) provide a large-scale check on inferred Northern and global fluxes when combined with global network (3) and airborne (2) data,and allow tests of our understanding through simulations of past and present conditions.

Goal 2: Program Elements 2, 3, 6, 9-11

The elements (9) surveys,time series, remote sensing, (10) a quantitative understanding of air-sea exchange processes,(2) airborne CO_2 observation program,and (3) global CO_2 monitoring network together address the first part of Goal 2: to quantify the oceanic uptake of CO_2: global ocean measurements.These elements provide direct long-term measurements defining sources and sinks on the scale of major ocean regions. A critically important task is to successfully integrate expanded observations of time series at key locations,observations of atmosphere-ocean exchange,periodic global ocean surveys, remote sensing of the oceans,large-scale airborne measurements over the oceans,and atmospheric data from island stations. The conceptual framework for interpreting these observations will be developed and tested in element (6), strategically planned regional observation experiments.

Ocean process studies and manipulations (10) tell us why the carbon is going (or coming from) major ocean regions and provide the basis for predicting long-term trends. Program elements (10) and (6) thus contribute significantly to the second part of Goal 2:to understand the mechanisms of oceanic uptake of CO_2.

Modeling and synthesis (11) provide large-scale checks on inferred oceanic and global fluxes,especially when exercised to provide global constraints using data from the global surface and airborne networks (elements (2) and (3). Models allow tests of our understanding through simulations of past disturbances,such as major El Niño-Southern Oscillation (ENSO) events.

Goal 3: Program Elements 1, 4, 5, 7, 11

The program elements (5) (reconstruct historical land use) and (4) (expand global terrestrial carbon and land use inventories) are specifically designed to address Goal 3: to determine the impact of historical and current land use. The expanded flux network (1),long-term terrestrial observations (7), and terrestrial process studies and manipulations (8) will provide integral checks and constraints on the interpretation of results from (4) and (5). Modeling and synthesis (11) will be the major tools bringing together the data and concepts developed by these program elements.

Goal 4: Program Element 11 (integrating elements 1-10)

The program element modeling and synthesis (11) represents the most comprehensive and integrating tool for Goal 4,projecting future atmospheric concentrations of CO_2. This goal is a major scientific undertaking,in which the models and analysis must be closely integrated with all other elements of the CCSP. To succeed, responsible agencies will need to develop a managerial framework with a unified vision of the program and with greatly enhanced mutual collaboration and strategic planning.

Goal 5: The Entire CCSP (all elements, integrated and coordinated)

Goal 5—developing the scientific basis for evaluating management decisions relating to CO_2 in many critical ways represents the culmination of the entire Carbon Cycle Science Plan. The ultimate measure of a successful carbon cycle research program will be found in its ability to provide practical answers to both scientific and societal questions.

Chapter 6: Program Implementation and Critical Partnerships

Implementation Principles

Past experience with large-scale, multidisciplinary global change research programs has provided invaluable insights into principles for successful program implementation. During its deliberations, the authors of this report (the Carbon and Climate Working Group) and sponsoring agencies of the U.S. Global Change Research Program (USGCRP) identified many aspects of the successful Tropical Ocean–Global Atmosphere (TOGA) Program as possible models for the Carbon Cycle Science Plan. Many of the principles and strategies described in this chapter have their roots in the TOGA Program and are drawn from the experiences of Working Group members, sponsoring agency representatives, and community colleagues, including a 1996 National Research Council review of the TOGA Program (NRC 1996). Working Group deliberations and discussions at the August 1998 Carbon Cycle Science Planning Workshop identified the following key principles for program implementation.

Shared Scientific Vision

This plan represents the critical first step in any successful global change research program—the development of a shared program vision focused on clearly defined problems with identifiable deliverables of value to both the scientific community and the potential beneficiaries in the public and private sectors. Development of this shared vision should involve broad community participation in an open process, with programmatic flexibility to evolve continually as new scientific insights emerge, new technologies are developed, and new information needs are identified.

In this context, the Working Group felt it essential to provide a clear statement of scientific priorities for a focused Carbon Cycle Science Program, while recognizing the critical contributions of related national and international global change research programs. These programs also address such issues as ecosystem dynamics, land use/land cover change, climate variability and change, and atmospheric chemistry. The Carbon Cycle Science Program proposed here describes the essential elements of a program designed specifically to improve the quantitative characterization of past and present CO_2 sources and sinks; to develop models to predict future sources and sinks; and to provide a scientific basis for evaluating potential carbon sequestration strategies and for measuring net emissions from major regions of the world.

Shared Programmatic Responsibility

The National Research Council's review of the TOGA Program (NRC 1996) points to the importance of implementing this shared scientific vision through a dynamic, interactive partnership between the scientific community and responsible federal agencies. In this partnership, responsibility for program direction, implementation, and review is shared, and all partners commit to the programmatic discipline needed to implement the shared vision of the program. As seen in TOGA, commitment to a shared scientific vision requires that, once a Carbon Cycle Science Plan has been adopted, the federal agencies agree that resources will be secured and allocated in accordance with the plan. The scientific community must also accept an appropriate level of responsibility for setting priorities, sustaining relevant existing commitments, and making a compelling case for new resources.

As was the case in TOGA, the programmatic partnership proposed here requires a strong mechanism for interagency coordination to take inventory of individual agency assets and ongoing programs. Agencies must also agree on appropriate agency roles and responsibilities for implementing elements of the Carbon Cycle Science Program, based on the agencies' individual capabilities and missions. Resources can, and probably should, remain in individual agencies, provided that participating agencies agree to a single plan, a single committee for the program's scientific oversight and review, a unified proposal/program review process, and a single address for scientific community and public access to information about the program. When successfully implemented, this ensures that funding decisions reflect scientific merit and programmatic relevance and are essentially "independent" of agency boundaries. The program management structure proposed later in this chapter is based on this model of interagency coordination.

Program Integration

Like the TOGA Program, the Carbon Cycle Science Program necessitates an integrated approach, combining sustained measurements and data analysis and synthesis; targeted process studies and field research campaigns; organized modeling and prediction efforts; and information management. In addition to requiring good integration among these programmatic activities, a successful Carbon Cycle Science Program will require a multidisciplinary approach. It is critical to integrate studies of atmospheric, oceanic, and terrestrial components of the carbon cycle, together with research on the human dimensions of carbon cycle changes.

Scientific Guidance and Review

Experience with numerous global change research programs has demonstrated the importance of establishing clear procedures for scientific guidance and review of the Carbon Cycle Science Program from the outset. In the case of TOGA, an NRC panel (under the auspices of the Climate Research Committee of the Board on Atmospheric Sciences and Climate) provided a source of ongoing scientific guidance and review throughout the program's lifetime. The Working Group recommends separating the scientific guidance and review processes in a structure that draws from both the TOGA experience and the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS) experiences. We recommend that an independent Scientific Steering Committee be responsible for scientific guidance. (The formation and composition of this committee is addressed in the section on proposed management structure below.) In addition, the Working Group recommends a periodic (e.g., every three to five years) external review of the Carbon Cycle Science Program. The Working Group suggests that the NRC Committee on Global Change Research is an appropriate body to oversee the conduct of these periodic reviews of issues related to scientific quality, relevance, accomplishments, future plans, and program implementation.

Links to International Programs

As the TOGA Program demonstrated, establishing strong ties to the related scientific efforts of other countries and formal international research programs (the World Climate Research Program in the case of TOGA) can yield significant benefits; it represents another key principle for successful implementation of the Carbon Cycle Science Program. The case for international collaboration is even stronger for carbon cycle research in light of the ongoing efforts of the Intergovernmental Panel on Climate Change and current national and international deliberations related to the United Nations Framework Convention on Climate Change. Establishing and sustaining effective links with related international programs is described in further detail below under "Critical Partnerships."

Access to Data and Communication of Research Results

Achieving the goals described in this plan requires a culture of open exchange of observations and associated data products, research findings, and model results. In part, this requirement calls for a new level of collaboration among scientists engaged in modeling, measurement programs, and field research. In this context, the Working Group notes that early and continuous investment in data-model integration and synthesis is essential to providing a full understanding of past, present, and future carbon cycle behavior. A commitment to easy and open access also implies greater responsibilities for information management strategy to ensure timely provision of data, research findings, and model results; to assimilate/integrate observations and data from different platforms, instruments, and field campaigns; to adhere to appropriate standards, protocols, and guidelines; and to provide metadata critical to the analysis from numerous individual scientists and participating institutions. The continuation of support for any research group under this plan will depend on the timely and complete availability of data and models generated.

Experience with other multidisciplinary, global change research programs like WOCE and TOGA highlights the technical challenges and opportunities associated with open access and exchange within the scientific community. The Carbon Cycle Science Program described in this plan, however, places an additional burden of responsibility on the scientific community and sponsoring agencies: effective communication of research results to intended users such as businesses, communities, land management agencies, and government officials. The U.S. Global Change Research Program uses the term "assessment" when describing such an organized effort to convey scientific results to potential beneficiaries in useful forms and to establish a continuing, interactive dialogue with those users. Current national and international discussions relating to the Framework Convention on Climate Change highlight the importance of sustaining a dialogue that provides government and private sector decision makers with reliable, quantitative information on the sources and sinks of carbon dioxide, both present and future. One element of this dialogue will involve scientific support for formal assessment programs such as the work of the Intergovernmental Panel on Climate Change. In addition, participants in the Carbon Cycle Science Program should, from the beginning, plan an organized program of communication, outreach, and education that supports the understanding and dissemination of new scientific insights and research results to interested parties in and beyond the scientific community.

Proposed Program Management Structure

With these principles in mind, the Working Group recommends establishment of a collaborative management structure for the Carbon Cycle Science Program as depicted in Figure 6.1.

This tripartite management structure reflects the shared responsibilities of the scientific community and the spon-

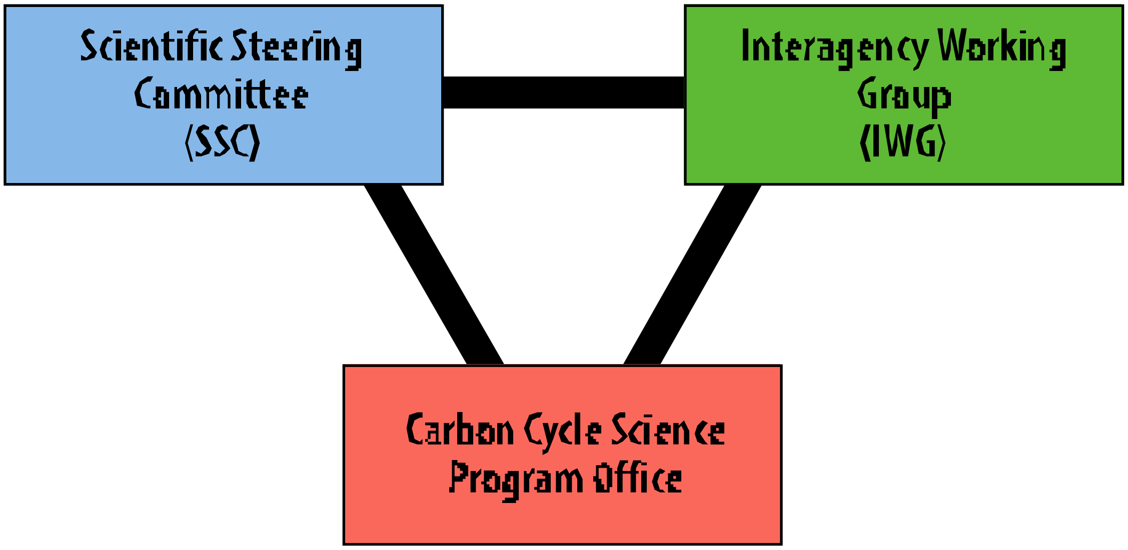


Figure 6.1 Carbon Cycle Science Program management structure.

soring federal agencies, and provides a mechanism to coordinate their contributions. While each component of the management structure has primary responsibility for different elements of the program, success requires that these management components work in unison, interacting on a day-to-day basis, exchanging information freely and openly, and jointly resolving critical issues and problems. The program will stand only if all three "legs" are balanced, strong and positioned to support their special responsibilities.

Responsibility for continuous scientific guidance would be provided by a Scientific Steering Committee (SSC) comprised of an expert panel actively engaged in various aspects of carbon cycle science. Individual members of the SSC would be selected by the sponsoring federal agencies in consultation with the scientific community and other interested parties. The NRC, through the Committee on Global Change Research, could be a source of nominations and/or review of a membership slate for the proposed SSC. Members of the steering committee should have a vested interest in the success of the program, and therefore, committee membership should likely include funded participants in the Carbon Cycle Science Program. Membership should reflect both individual disciplinary/programmatic expertise and the special challenges posed by the integrated nature of the program described in this plan. In addition, consideration should be given to including individuals who represent potential beneficiaries of the program in government, the private sector, and public interest groups.

Working with their colleagues in the sponsoring federal agencies, the SSC would have primary responsibility for ensuring that the detailed implementation of the Carbon Cycle Science Program follows directly from the scientific goals and programmatic objectives described in the plan. The SSC would achieve this by continually evaluating progress; by reviewing priorities and revising plans as needed to reflect new scientific insights, technology, and information needs; by evaluating proposals for major adjustments to measurement, field research, and modeling projects, ensuring a strong scientific review process for individual projects; and by periodically submitting the Carbon and Climate Science Program to rigorous review by an outside body. The Working Group recommends that the sponsoring federal agencies look to the NRC's Committee on Global Change Research to organize periodic (e.g., every three to five years) outside reviews of the Carbon Cycle Science Program.

An Interagency Working Group (IWG) comprised of agencies contributing resources to support the Carbon Cycle Science Program would have responsibility for interagency coordination and program management. The IWG would have primary responsibility for identifying and sustaining relevant existing commitments and securing appropriate resources for new activities in support of the program. As for the TOGA Program, the IWG for the Carbon Cycle Science Program should be comprised of program managers with the responsibility and authority to commit resources in support of the program. The IWG should have access to the scientific expertise residing in individual agencies, and IWG members should have the responsibility of ensuring that their agency assets—fiscal, human, and capital—are brought to bear appropriately in support of the program. In addition to their responsibilities for communication within and among the participating scientific agencies, IWG members will also be responsible for ensuring that program results are incorporated appropriately into federal policy formulation and mission agency decision making. Similarly, as public servants, members of the IWG have a special responsibility for communicating the results of the Carbon Cycle Science Program to interested parties in the public and private sector.

One of the IWG's most important initial tasks will be identifying existing agency assets (human, programmatic, and fiscal) and agreeing on individual agency roles and responsibilities in implementing the shared scientific vision described in this plan. Agency responsibilities for the Carbon Cycle Science Program should properly reflect agency missions, expertise, and experience. By way of example, discussions during the August 1998 Workshop on Carbon Cycle Science highlighted the following potential roles for individual agencies. The National Science Foundation would continue its tradition of support for critical long-term field studies and laboratory experiments to illuminate key processes for carbon cycle and Earth system modeling, and seek funding for exploratory research by individual investigators representing a variety of viewpoints and approaches. Operational mission agencies such as the National Oceanic and Atmospheric Administration, U.S. Geological Survey, and U.S. Department of Energy might play critical roles in supporting sustained measurements and integrated, predictive modeling projects. Resource management agencies such as the Department of Interior, Department of Energy, and the Department of Agriculture might assume primary responsibility for examining the roles of terrestrial reservoirs for carbon dioxide and the impacts of human activities on terrestrial ecosystems. The National Aeronautics and Space Administration might provide the lead in applications of space-based, remote-sensing techniques and technologies for carbon cycle science. None of these responsibilities would be exclusive, but some identification of appropriate, individual agency roles will be essential to successful implementation of an integrated interagency program.

Once the sponsoring federal agencies and the scientific community have adopted a shared scientific vision for the program and reached agreement on individual agencies' roles, the IWG would be responsible for overseeing the joint implementation of the Carbon Cycle Science Program on behalf of the participating federal agencies. We would like to emphasize that joint implementation does not necessarily require pooling of resources or the designation of a single "lead agency." However, it does require a joint commitment and adherence to the shared scientific vision (as described in the Carbon Cycle Science Plan) and to a primary source of scientific advice (the SSC described above); to the implementation of a consistent and unified approach to proposal and program review processes; and to the provision of a clear point of contact for and source of information on the Carbon Cycle Science Program. In addition, the IWG would likely constitute the primary liaison between the carbon cycle science community and government policy officials and resource management agencies in the federal government.

Managing the day-to-day implementation of this partnership between the scientific community and the sponsoring federal agencies would be the responsibility of a Carbon Cycle Science Program Office. Responsibility for this component of the program management structure could, as in the case of TOGA, reside within a federal agency or, as in the WOCE program, be assigned through a competitive process to a qualified scientific institution outside the government. As envisioned by this Working Group, the function of the Carbon Cycle Science Program Office should not require establishing a large bureaucracy or the expenditure of a significant level of resources. Some investment of resources (human and fiscal) will be required, however, to ensure that the Program Office can effectively provide the programmatic and institutional "glue" to sustain the critical interaction between the scientific community and federal agencies responsible for implementation of the program. The Carbon Cycle Science Program Office staff should have appropriate levels of scientific and programmatic expertise (e.g., a Ph.D. or equivalent experience).

Specific responsibilities of the Program Office would include providing a programwide point of contact and source of information on program direction, activities, status, and accomplishments; providing programwide liaison with the National Research Council's Committee on Global Change Research and other relevant scientific organizations and research programs; serving as primary liaison for the U.S. program with relevant international scientific programs; supporting the day-to-day aspects of program implementation, assisting in program development, resource management, and program evaluation efforts; and providing secretariat services for both the SSC and the IWG.

Critical Partnerships

Successful implementation of the Carbon Cycle Science Program described in this plan will require the creation and maintenance of a number of critical partnerships. First and foremost, the program should represent a dynamic and innovative partnership between the scientific community and the sponsoring agencies in the federal government. The proposed management structure described above reflects this partnership and a shared responsibility for ensuring scientific quality and programmatic relevance, setting priorities, adhering to plans, securing required resources, and interpreting and disseminating the scientific and information products that emerge from the Carbon Cycle Science Program.

The Working Group believes that implementation of the program described in this plan would benefit significantly from efforts to build sustained partnerships between federal laboratories and the extramural research community, leveraging the special capabilities and expertise of those partners. For example, partnership in the design, development, testing, and deployment of measurement systems could help address a number of issues facing the scientific community today. This partnership could ensure an appropriate mix of researchers aware of the scientific requirements, and engineers and technicians familiar with system capabilities; and facilitate the exchange of ideas and experience among groups working on the development of systems to meet similar needs. In short, it could create an environment of creative synergy rather than simply duplicate effort. The Carbon Cycle Science Program envisioned in this plan provides a framework for creative new partnerships among various disciplines and programmatic areas of expertise—such as individuals involved in measurements, modeling, and process research—within the scientific community. Similarly, innovative partnerships among supporting federal agencies should bring individual agency assets and expertise to bear on a shared program in complementary ways that build on existing capabilities, leverage limited resources, avoid duplication, and produce new opportunities for scientific progress.

The global nature of the carbon cycle and the international context of current policy deliberations related to CO_2 and other greenhouse gases highlight the critical need for international collaboration in carbon cycle investigations. As has been the case in the past, a strong U.S. program can serve as a catalyst for similar programs in other countries and provide a focal point for international coordination. Such multinational collaboration offers opportunities to leverage resources and take advantage of comparable methodologies and joint projects. Early collaboration with Canada, for example, could produce significant benefits for proposed investigations of the North American terrestrial sink. Similarly, investigations of ocean sources and sinks in the Pacific will benefit from international collaboration in much the same way that TOGA's investigations of El Niño benefited from the contributions of partners around the Pacific Basin and throughout the world.

As has also been seen in programs like TOGA, WOCE, and JGOFS, one particularly beneficial approach to international partnerships involves the development and implementation of strong U.S. contributions to established international global change research programs. The Carbon Cycle Science Program should establish strong ties to the World Climate Research Program (particularly the CLIVAR Program), the Global Energy Water Cycle Experiment (GEWEX), the International Geosphere–Biosphere Programme (IGBP, particularly JGOFS, GAIM, and IGAC), and the International Human Dimensions of Global Change Program (particularly the Land Use/Land Cover Change project being implemented jointly with IGBP). In addition, the sustained measurement components of the program described in this plan could provide substantial contributions to emerging global observing programs such as the Global Climate Observing System (GCOS), the Global Ocean Observing System (GOOS), and the Global Terrestrial Observing System (GTOS). Conversely, these emerging multinational endeavors could leverage resources (such as space- and ground-based observational platforms); develop and demonstrate new technologies; and provide a global, Earth system context for carbon cycle measurements emphasizing large-scale ecosystem dynamics and carbon cycle interactions with variability and change in the climate system.

Finally, the Working Group believes that the Carbon Cycle Science Program described here would benefit from an early and sustained partnership with the private sector. Some of the program's goals—notably, providing a scientific basis for evaluating potential carbon sequestration strategies and measuring net emissions at a regional scale—should be of interest and value to businesses involved in the energy sector, resource use and management (e.g., forestry), and agriculture, for example. Private sector expertise and assets in technology R&D could accelerate the development and demonstration of critical new measurement technologies. Scientists interested in the design, development, testing and deployment of measurement systems face a number of obstacles today, and this Working Group believes that innovative partnerships among federal laboratories, universities, and the private sector (in the U.S. and abroad) would be mutually beneficial. Investments in the development of new systems should be supplemented with resources to make use of commercially available measurement systems in the field. Decisions to support the development of new systems should represent a commitment of the time and resources required to take new instrumentation from concept to reality. Early involvement of the private sector in this process could help ensure a smooth transition from limited experimental prototype to commercially available (and affordable) technology to support broad community needs.

Joint implementation of carbon cycle measurement programs and collaborative development of integrated modeling and assessment capabilities could result in early progress, with direct benefits to the scientific community, public policy officials, and private sector interests directly affected by carbon cycle and climate policies. The Working Group was unable to engage in detailed discussion of the character of such a public-private partnership in carbon cycle research during this initial planning phase. But we strongly encourage a thorough exploration of the challenges and opportunities of partnership with the private sector as an early implementation task.

Bibliography

Archer, D.,H.Kheshgi and E.Maier-Reimer, Multiple Timescales for the Neutralization of Fossil Fuel CO_2, *Geophys.Res.Lett., 24*, 405-408,1997.

Archer, S., D. S.Schimel and E.A.Holland,Mechanisms of shrubland expansion:Land use, climate or CO_2, *Climatic Change, 29*, 91-99,1995.

Aumont, O, J. C.Orr, D. Jamous, P. Monfray, O. Marti,and G. Madec,A degradation approach to accelerate simulations to steady-state in a 3-D tracer transport model of the global ocean, *Climate Dynamics, 14*, 101-116, 1998.

Baar, H. J.W. d., J.T. M.d. Jong, D. C.E.Bakker, B.M.Löscher, C.Veth, U. Bathmann and V. Smetacek,Importance of iron for plankton blooms and carbon dioxide drawdown in the Southern Ocean, *Nature, 373*, 412-415, 1995.

Bacastow. R.and C.D. Keeling,Atmospheric carbon dioxide and radiocarbon in the natural carbon cycle. II, Changes from A.D. 1700 to 2070 as deduced from a geochemical reservoir. In: G.M.Woodwell and E.V. Pecan (eds.) Carbon and the Biosphere. U.S.Dept.of Commerce (Springfield,Virginia),86-135,1973.

Bakwin, P. S., P. P.Tans,C.Zhao, W. Ussler and E.Quesnell, Measurements of carbon dioxide on a very tall tower, *Tellus, 47B*, 535-549,1995.

Bakwin, P.S., P.P.Tans, D. F. Hurst,and C.Zhao, Measurements of carbon dioxide on very tall towers: results of the NOAA/CMDL program. *Tellus, 50B*, 401-415,1998.

Baldocchi, D.,Valentini,R.,Running,S.,Oechel, W. and R. Dahlman, Strategies for measuring and modeling carbon dioxide and water vapor fluxes over terrestrial ecosystems, *Global Change Biology 2*, 159-169,1996.

Barnola, J. M., D. Raynaud, Y. S. Korotkevich and C.Lorius, Vostok ice core provides 160,000-year record of atmospheric CO_2, *Nature, 329*, 408-414,1987.

Bates, N. R.,A. F. Michaels and A.H.Knap,Seasonal and interannual variability of the oceanic carbon dioxide system at the U. S.JGOFS Bermuda Atlantic time-series study site, *Deep-Sea Res., Part II*, 1996.

Battle,M.,M.Bender,T. Sowers, P. P.Tans, J. H.Butler, J.W. Elkins, J.T. Conway, N. Zhang, P. Lang and A.D. Clarke, Atmospheric gas concentrations over the past century measured in air from firn at the South Pole, *Nature, 383*, 2312-235,1996.

Behrenfeld,M. J. and P. G. Falkowski,A consumers guide to phytoplankton primary production models, *Limnol. Oceanogr., 42*, 1479-1491,1997.

Bender, M.L.,T. Sowers, J. N. Barnola and J. Chappellaz, Changes in the O_2/N_2 ratio of the atmosphere during recent decades reflected in the composition of air in the firn at Vostok Station,Antarctica, *Geophys.Res.Lett., 21*, 189-192,1994.

Berner, R.A.,Geocarb II: A revised model of atmospheric CO_2 over Phanerozoic time, *Am. J. Sci.*, 294,56-91, 1994.

Billings, W. D., J. O. Luken, D. A.Mortensen and K.M. Peterson,Arctic tundra:a source or sink for atmospheric carbon-dioxide in a changing environment, *Oecologia, 53*, 7-11,1982.

Blunier,T., J. Chappellaz, J. Schwander, A.Dallenback,B. Stauffer,T. F. Stocker, D. Raymond, J. Jouzel,H.B.Clausen, C. U. Hammer and S. J. Johnson,Asynchrony of Antarctica and Greenland climate during the last glacial, *Nature*, 1-18,1998.

Bolin,B.Changes of land biota and their importance for the carbon cycle, *Science, 196*, 613-615,1977.

Brewer, P. G.,C.Goyet and D. Dyrssen,Carbon dioxide transport by ocean currents at 25-N latitude in the Atlantic Ocean, *Science, 246*, 477-479,1989.

Broecker, W. S.and T.-H. Peng,Interhemispheric transport of carbon dioxide by ocean circulation, *Nature, 356*, 587-589,1992.

Brook,E. J.,T. Blunier and e.al.,Rapid variations in atmospheric methane concentration during the past 110,000 years, *Science, 273*, 1087-1091,1993.

Cao,M.and F. I. Woodward,Dynamic response of terrestrial ecosystem carbon cycling to global climate change, *Nature, 393*, 249-252,1998.

Chadwick, O.A.,L.A.Derry, P. M.Vitousek,B. J. Huebert and L. O. Hedin,Changing sources of nutrients during four million years of ecosystem development, *Nature, 397*, 491-497,1999.

Chappellaz, J.,T. Blunder, D. Raynaud, J. M.Barnola, J. Schwander and B.Stauffer, Synchronous changes in atmospheric CH_4 and Greenland climate between 40 and kyr BP, *Nature, 366*, 443-455,1993.

Chou, W.W.,Estimation of Net Regional Surface Fluxes of CO_2 and O_3 Over Amazonia from Aircraft Data,1999.

Ciais, P., P. P. Tans, M. Trolier, J. W. C. White and R. J. Francey, A large Northern Hemisphere terrestrial CO_2 sink indicated by the $^{13}C/^{12}C$ ratio of atmospheric, *Science, 269*, 1098-1102, 1995a.

Ciais, P., P. P. Tans, J. W. C. White, M. Trolier, R. J. Francey, J. A. Berry, D. R. Randall, P. J. Sellers, J. G. Collatz and D. S. Schimel, Partitioning of ocean and land uptake of CO_2 as inferred by _13C measurements from the NOAA Climate Monitoring and Diagnostics Laboratory Global Air Sampling, *J. Geophys. Res., 100*, 5051-5070, 1995b.

Coale, K.H., K.S. Johnson, S.E. Fitzwater, R.M. Gordon, S. Tanner, F. P. Chavez, L. Ferioli, C. Sakamoto, P. Rogers, F. Millero, P. Steinberg, P. Nightingale, D. Cooper, W. P. Cochlan, M.R. Landry, J. Constantinou, G. Rollwagen, A. Trasvina and R. Kudela, A massive phytoplankton bloom induced by an ecosystem-scale iron fertilization experiment in the equatorial Pacifc Ocean, *Nature, 383*, 495-501, 1996.

Dai, A. and I. Y. Fung, Can climate variability contribute to the “missing” CO_2 sink?, *Global Biogeochem. Cycles, 7*, 599-609, 1993.

Dansgaard, W., S. J. Johnsen, J. B. Clausen, D. Dahl-Jensen, N. S. Gundestrup, C. U. Hammer, C.S. Hvidberg, J. P. Steffensen, A.E. Sveinbjornsfottir, J. Jouzel and G. Bond, Evidence for general instability of past climate from a 250-kyr ice-core record, *Nature, 364*, 218-220, 1993.

DeGrandpre, M. D., T. R. Hammar, S. P. Smith and F. L. Sayles, In situ measurements of seawater pCO_2, *Limnol. Oceanogr., 40*, 969-975, 1995.

Denman, K., E. Hofmann and H. Marchant, Marine biotic responses to environmental change and feedbacks to climate, in *Climate Change 1995*, vol. edited by J. T. Houghton, L. G. M. Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell, 483-516, Cambridge University Press, New York, 1996.

Denning, A.S., M. Holzer, K.R. Gurney, M. Heimann, R.M. Law, P. J. Rayner, I. Y. Fung, S.-M. Fan, S. Taguchi, P. Friedlingstein, Y. Balkanski, M. Maiss and I. Levin, Three-dimensional transport and concentration of SF6: A model intercomparison study (TransCom 2), *Tellus, in press*, 1999.

Desjardins, R.L., J. L. MacPherson, L. Mahrt, P. Schuepp, E. Patty, H. Neumann, D. Baldocchi, S. Wofsy, D. Fitzjarrald, H. McCaughey, and D. W. Joiner, Scaling up flux measurements for the boreal forest using aircraft-tower combinations. *J. Geophys. Res. 102*, 29125-29134, 1997.

Dixon, R.K., S. Brown, R.A. Houghton, A.M. Solomon, M.C. Trexler and J. Wisniewski, Carbon pools and flux of global forest ecosystems, *Science, 263*, 185-190, 1994.

Doney, S.C., D. M. Glover and R. G. Najjar, A new coupled, one-dimensional biological-physical model for the upper ocean: applications to the JGOFS Bermuda Atlantic Time Series (BATS) Site, *Deep Sea Res., 43*, 591-624, 1996.

Esbensen, S.K., and Y. Kushnir, The heat budget of the global ocean: An atlas based on estimates from surface marine observations, *Climatic Research Institute Report 29*, Oregon State University, Corvallis, OR.

Etheridge, D. M., L. P. Steele, R.L. Langenfelds and R. J. Francey, Natural and anthropogenic changes in atmospheric CO_2 over the last 1000 years from air in Antarctic ice and firn, *J. Geophys. Res., 101*, 4115-4128, 1996.

Falkowski, P. G., Evolution of the nitrogen cycle and its influence on the biological sequestration of CO_2 in the ocean, *Nature, 387*, 272-274, 1997.

Falkowski, P. G., Ironing out what controls primary production in the nutrient rich waters of the open ocean, *Global Change Biology, 1*, 161-163, 1995.

Falkowski, P. G., R. T. Barber and V. Smetacek, Biogeochemical controls and feedbacks on ocean primary production, *Science, 281*, 200-206, 1998.

Fan, S.-M., M. Gloor, J. Mahlman, S. Pacala, J. L. Sarmiento, T. Takahashi and P. Tans, A large terrestrial carbon sink in North America implied by atmospheric and oceanic CO_2 data and models, *Science, 282*, 442-446, 1998.

FAO, World Agriculture: Towards 2010 - An FAO Study, in vol. edited by 14-23, John Wiley and Sons, West Sussex, 1995.

Fasham, M. J. R., Variations in the seasonal cycle of biological production in subarctic oceans: A model sensitivity analysis, *Deep Sea Res., 42*, 1111-1150, 1995.

Feely, R.A., R. Wanninkhof, C.E. Cosca, P. M. Murphy, M. F. Lamb and M. D. Steckley, CO_2 distributions in the equatorial Pacific during the 1991-1992 ENSO event, *Deep Sea Res., 42*, 365-386, 1995.

Feely, R.A., R. Wanninkhof, C.E. Coscas, M. J. McPhaden, R. H. Byrne, F. J. Millero, F. P. Chavez, T. Clayton, D. M. Campbell and P. P. Murphy, The effect of tropical instability waves on CO_2 species distributions along the equator in the eastern equatorial Pacific during the 1992 ENSO event, *Geophys. Res. Lett., 21*, 277-280, 1994.

Feely, R.A., R. Wanninkhof, C. Goyet, D. E. Archer and T. Takahashi, Variability of CO_2 Distributions and Sea-Air Fluxes in the Central and Eastern Equatorial Pacific During 1991-94 El Niño, *Deep Sea Res., 33*, 1996.

Foster, D. R.,Land-use history and transformations of the forest landscape of central New England,in *Humans as Components of Ecosystems: Subtle Human Effects and the Ecology of Populated Areas*, vol.edited by S.T. A.Pickett and M.McDonnell,91-110,Springer-Verlag, New York,1993.

Foster, D. R.,Land-use history and four hundred years of vegetation change in New England,in *Principles, Patterns and Processes of Land Use Change: Some Legacies of the Columbian Encounter*, vol.edited by B. L.Turner, 253-318, John Wiley and Sons, New York, 1995.

Francey, R. J., P. P. Tans,C.E.Allison,I. G. Enting, J. W. C. White and M. Troller, Changes in oceanic and terrestrial carbon uptake since 1982, *Nature*, *373*, 326-330,1995.

Frew, N. M.,The role of organic films in air-sea gas exchange,in *The Sea Surface and Global Change*, vol. edited by P. S.Liss and R.A.Duce,121-171,Cambridge University Press,Cambridge,1997.

Friederich, G. E., P. G. Brewer, R.Herlien and F. P. Chavez, Measurements of sea surface partial pressure of CO_2 from a moored buoy, *Deep Sea Res.*, *42*, 1175-1186, 1995.

Friedlingstein, P.,I.Fung,E.Holland, J. John, G. Brassuer, D. Erickson and D. Schimel,On the contribution of CO_2 fertilization to the missing biospheric sink, *Global Biogeochemical Cycles*, *9*, 541-556,1995.

Fung,I.,C.B. Field, J.A.Berry, M.V. Thompson, J.T. Randerson,C.M.Malmstrom, P.M. Vitousek, G.J. Collatz, P.J. Sellers, D.A.Randall,A.S.Denning, F. Badeck and J. John,Carbon-13 exchanges between the atmosphere and the terrestrial biosphere, *Global Biogeochem. Cycles*, *11*, 507-533,1997.

Gent, P. R., J.Willebrand,T. J. McDougall and J. C. McWilliams, Parameterizing eddy-induced tracer transports in ocean circulation models, *J. Phys.Oceanogr.*, *25*, 463-474,1995.

Goulden,M.L., J.W. Munger, S.M. Fan,B. C.Daube and S.C. Wofsy, Exchange of carbon dioxide by a deciduous forest: response to interannual climate variability, *Science*, *271*, 1576-1578,1996.

Goulden,M.L.,S.C. Wofsy, J.W. Harden,S.E. Trumbore, P. M. Crill,S.T. Gower,T. Fries, B.C.Daube,S.-M. Fan, D. J. Sutton,A.Bazzaz and J.W. Munger, Sensitivity of boreal forest carbon balance to soil thaw, *Science*, *279*, 214-217,1998.

Goyet,C., D. R. Walt and P. G. Brewer, Development of a fiber optic sensor for measurement of pCO_2 in sea water: design criteria and sea trials, *Deep Sea Res.*, *39*, 1015-1026,1992.

Gruber, N.,Anthropogenic CO_2 in the Atlantic Ocean, *Global Biogeochem.Cycles*, *12*, 165-192,1998.

Gruber, N., J. L.Sarmiento and T. F. Stocker, An improved method for detecting anthropogenic CO_2 in the oceans, *Global Biogeochem.Cycles*, *10*, 809-837,1996.

Hansell, D.A.and C.A.Carlson,Net community production of dissolved organic carbon. *Global Biogeochem. Cycles*, *12*, 443-453,1998.

Harden, J.W.,E.T. Sundquist,R. F. Stallard and R.K.Mark, Dynamics of soil carbon during deglaciation of the Laurentide Ice Sheet, *Science*, *258*, 1921-1924,1992.

Harrison, D. E.and D. S.Luther, Surface winds from tropical Pacific Islands - Climatological statistics, *Journal of Climate*, *3*, 251-271,1990.

Haywood, J. M.,R. J. Stouffer, R.T. Wetherald,S.Manabe and V. Ramaswamy, Transient response of a coupled model to estimate changes in greehouse gas and sulfate concentrations, *Geophys.Res.Lett.*, *24*, 1335-1338,1997.

Holfort, J.,K.M. Johnson,B.Schneider, G. Siedler and D.W. R. Wallace,The meridional transport of dissolved inorganic carbon in the South Atlantic Ocean, *Global Biogeochem.Cycles*, *12*, 479-499,1998.

Holland,E.A.,B.H.Braswell, J.-F. Lamarque,A. Townsend, J. Sulzman, J.-F. Muller, F. Dentener, G. Brasseru,H.L.II, J. E. Penner and G.-J. Roelofs, Variations in the predicted spatial distribution of atmospheric nitrogen deposition and their impact on carbon uptake by terrestrial ecosystems, *J. Geophys.Res.*, *102*, 15,849-15,866,1997.

Houghton, J.T.,L. G. M. Filho,B.A.Callander, N. Harris,A. Kattenberg and K.Maskell, *Climate Change 1995*, vol. pp.,Cambridge University Press,Cambridge,1996.

Houghton,R.A.,Is Carbon accumulating in the northern temperate zone?, *Global Biogeochem.Cycles*, *7*, 611-617,1993.

Houghton,R.A.,R. D. Boone, J. R. Fruci, J. E.Hobbie, J. M. Melillo,C.A. Palm,B. J. Peterson, G. R.Shaver, G. M. Woodwell,B.Moore, D. L.Skole and N. Myers,The flux of carbon from terrestrial ecosystems to the atmosphere in 1980 due to changes in land use: geographic distribution of the global flux, *Tellus*, *39B*, 122-139,1987.

Houghton,R.A.,E.A.Davidson and G. M. Woodwell, Missing sinks, feedbacks,and understanding the role of terrestrial ecosystems in the global carbon balance, *Global Biogeochem.Cycles*, *12*, 25-34,1998.

Houghton,R.A., J. E.Hobbie, J. M.Melillo,B.Moore,B. J. Peterson, G. R.Shaver and G. M. Woodwell,Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: A net release of CO_2 to the atmosphere, *Ecological Monographs*, *53(3)*, 235-262, 1983.

Hurst, D.F., P. S.Bakwin,R.C.Meyers,and J.W. Elkins, Behavior of trace gas mixing ratios on a very tall tower in North Carolina, *J. Geophys.Res.*, *102*, 8825-8835, 1997.

IGBP Terrestrial Carbon Working Group,The terrestrial carbon cycle:implications for the Kyoto Protocol, *Science*, *280*, 1393-1394,1998.

Indermühle,A., T. F. Stocker, F. Joos,H. Fischer, H. J. Smith,M. Wahlen,B.Deck, D. Mastroianni,T.Tschumi,T. Blunier, R. Meyer and B.Stauffer, Holocene carbon-cycle dynamics based on CO_2 trapped in ice at Taylor Dome,Antarctica, *Nature*, *398*, 121-126,1999.

Jähne,B.,K. O. Münnich,R.Bösinger,A.Dutzi, W. Huber and P. Libner, On parameters influencing air-water gas exchange, *J. Geophys.Res.*, *92*, 1937-1949,1987.

Jouzel, J., N. I.Barkov, J. M.Barnola,M.Bender, J. Chappellaz, G. Genthon,V. M. Kotlyakov,V. Lipenkov, C.Lorius, J. R. Petit, D. Raynaud, G. Raisbeck,C.Ritz,T. Sowers,M. Stievenard, F. Yiou and P. Yiou,Extending the Vostok ice-core record of paleoclimate to the penultimate glacial period, *Nature*, *364*, 407-412,1993.

Kamykowski, D. and S.-J. Zentara,Predicting plant nutrient concentrations from temperature and Sigma-T in the upper kilometer of the world ocean, *Deep Sea Res.*, *33*, 89-105,1986.

Karl, D.,R.Letelier, L.Tupas, J. Dore, J. Christian and D. Hebel,The role of nitrogen fixation in biogeochemical cycling in the subtropical North Pacific Ocean, *Nature*, *388*, 533-588,1997.

Karl, D.M.,A sea of change:Biogeochemical variability in the North Pacific subtropical gyre, *Ecosystems 2*:181-214,1999.

Kasischke,E.S., N. L.Christensen,and B.J. Stock, Fire, Global Warming,and the carbon balance of boreal forest. *Ecol.Appl. 5*, 437-451,1995.

Keeling,C. D.,R.B.Bacastow, A. F. Carter, S.C.Piper,T. P. Whorf, M.Heimann, W. G. Mook and H.Roeloffzen,A three-dimensional model of atmospheric CO_2 transport based on observed winds: 1 Analysis of observational data,in *Aspects of Climate Variability in the Pacific and the Western Americas AGU Monograph 55*, vol. edited by D. H. Peterson,165-236, AGU,Washington D.C.,1989.

Keeling,C. D.,T. P. Whorf, M. Wahlen and J.V. d.Plicht, Interannual extremes in the rate of rise of atmospheric carbon dioxide since 1980, *Nature*, *375*, 666-670, 1995.

Keeling,R. F. and T.-H. Peng,Transport of heat,CO_2 and O_2 by the Atlantic's thermohaline circulation, *Philosophical Transactions of the Royal Society*, *348*, 133-142,1995.

Keeling,R. F.,S.C.Piper and M.Heimann,Global and hemispheric CO_2 sinks deduced from changes in atmospheric O_2 concentration, *Nature*, *381*, 218-221,1996.

Keeling,R. F. and S.R.Shertz,Seasonal and interannual variations in atmospheric oxygen and implications for the global carbon cycle, *Nature*, *358*, 723-727,1992.

Lal,R., J. M.Kimble,R. F. Follett and C. V. Cole, *The Potential of U.S.Cropland to Sequester Carbon and Mitigate the Greenhouse Effect*, vol.pp.,Ann Arbor Press,Chelsea,Michigan,1998.

Landry, M.R.et al.,Iron and grazing constraints on primary production in the central equatorial Pacific. An EqPac synthesis, *Limnol.Oceanogr.*, *42*, 405-418,1997.

Law, R.M., P. J. Rayner,A.S.Denning, D. Erickson,I. Y. Fung, M.heimann,S.C.Piper, M.Ramonet,S. Taguchi, J.A. Taylor, C.M.Trudinger and I. G.Watterson,Variations in modeled atmospheric transport of carbon dioxide and the consequences for CO_2 inversions, *Global Biogeochem.Cycles*, *10*, 783-796,1996.

Lloyd, J.,B.Kruijt, D.Y. Hollinger, J. Grace,R. J. Francey, S.-C. Wong, F. M. Kelliher,A.C.Miranda,and E.-D. Schwartz, Vegetation effects on the isotopic composition of atmospheric CO_2 at local and regional scales: Theoretical aspects and a comparison between rain forest in Amazonia and a boreal forest in Siberia, *Australian J. Plant Physiology*, *23*, 371-399,1996.

Lloyd, J. and G. Farquahar, ^{13}C Discrimination during CO_2 assimilation by the terrestrial biosphere. *Oecologia*, *99*, 201-215,1994.

Luz,B.,E.Barkan,M.Bender, M.Thiemens and K.Boering, Triple-isotope composition of atmospheric oxygen as a tracer of biosphere productivity, *Nature*, *400*, 547-550, 1999.

Madec, G.,and M.Imbard,A global ocean mesh to overcome the North Pole singularity, *Climate Dynamics*, *12*, 381-388,1996.

Maier-Reimer, E.,Geochemical cycles in an ocean general circulation model:Preindustrial tracer distributions, *Global Biogeochem.Cycles*, *7*, 645-677,1993.

Maier-Reimer, E.and K.Hasselmann,Transport and storage of CO_2 in the ocean - an inorganic ocean-circulation carbon cycle model, *Clim.Dyn.*, *2*, 63-90,1987.

Manabe,S.and R. J. Stouffer, Multiple century response of a coupled ocean-atmosphere model to an increase of atmospheric carbon dioxide, *Journal of Climate*, *7*, 5-23,1994.

Marenco, A., V. Thouret, P. Nédélec, H. Smit, M. Helten, D. Kley, F. Karcher, P. Simon, K. Law, J. Pyle, G. Poschmann, R. Von Wrede, C. Hume, and T. Cook, Measurement of ozone and water vapor by Airbus in-service aircraft: The MOZAIC airborne program, An overview, *J. Geophys. Res.*, *103*, 631-625, 1998.

Marland, G., R. J. Andres, and T. A. Boden. Global, regional, and national CO_2 emissions, In: Trends '93, T. A. Boden, D. P. Kaiser, R. J. Sepanski, and R. W. Stoss, (Eds.), publication No. ORNL/CDIAC-65, Carbon Dioxide Information Center, Oak Ridge National Laboratory, Oak Ridge, TN, pp. 505-581, 1994.

Martin, J. H., Glacial-interglacial CO_2 change: the iron hypothesis, *Paleoceanography*, *5*, 1-13, 1990.

Martin, J. H., Iron, Liebig's Law and the greenhouse, *Oceanography*, *4*, 52-55, 1991.

Matear, R. J. and A. C. Hirst, Climate change feedback on the future oceanic CO_2 uptake, *Tellus*, in press.

McGowan, J. A., D. R. Cayan, and L. M. Dorman, Climate ocean variability and ecosystem response in the Northeast Pacific, *Science*, *281*, 210-217, 1998.

Melillo, J. et al., Land-use change in the Soviet Union between 1850 and 1980: causes of a net release of CO_2 to the atmosphere, *Tellus*, *40B*, 116-128, 1988.

Merlivat, L. and P. Brault, CARIOCA buoy: Carbon dioxide monitor, *Sea Technology*, *10*, 23-30, 1995.

Michaels, A. F., D. Olsen, J. Sarmiento, J. Ammerman, K. Fanning, R. Jahnke, A. H. Knap, F. Lipschultz and J. Prospero, Inputs, losses and transformations of nitrogen and phosphorus in the pelagic North Atlantic Ocean, *Biogeochemistry*, *35*, 181-226, 1996a.

Michaels, A. F., J. L. Sarmiento and J. Prospero, Excess nitrate and the rate of nitrogen fixation in the Sargasso Sea, *EOS*, *76*, OS84, 1996b.

Myneni, R. B., C. D. Keeling, C. J. Tucker, G. Asrar and R. R. Nemani, Increased plant growth in the northern high latitudes from 1981 to 1991, *Nature*, *386*, 698-702, 1997.

National Research Council, *Global Environmental Change: Research pathways for the next decade*, National Academy Press, Washington, D.C., 1998.

National-Research-Council, *Learning to Predict Climate Variations Associated with El Niño and the Southern Oscillation: Legacies of the TOGA Program*, vol. pp., National Academy Press, Washington, D.C., 1996.

Nilsson, S. and W. Schopfhauser, The carbon-sequestration potential of a global afforestation program, *Climatic Change*, *30*, 267-293, 1995.

Oechel, W. C., S. J. Hastings, G. Vourltis, M. Jenkins, G. Riechers and N. Grulke, Recent Changes of Arctic Tundra Ecosystems from a Net Carbon Dioxide Sink to a Source, *Nature*, *361*, 520-523, 1993.

Oeschger, H., U. Siegenthaler, U. Schotterer and A. Gugelmann, A box diffusion model to study the carbon dioxide exchange in nature, *Tellus*, *27*, 168-192, 1975.

Potosnak, M. J., S. C. Wofsy, A. S. Denning, T. J. Conway, and D. H. Barnes, Influence of biotic exchange and combustion sources on atmospheric CO_2 concentrations in New England from observations at a forest flux tower. *J. Geophys. Res.*, in press, 1999.

Quay, P. D., B. Tilbrook, and C. S. Wong, Oceanic uptake of fossil fuel CO_2: Carbon-13 evidence, *Science*, *256*, 74-79, 1992.

Randerson, J. T., M. V. Thompson, T. J. Conway, I. Y. Fung and C. B. Field, The contribution of terrestrial sources and sinks to trends in the seasonal cycle of atmospheric carbon dioxide, *Global Biogeochem. Cycles*, *11*, 535-560, 1997.

Raschi, A., F. Milietta, R. Tognetti and P. R. v. Gardigen (Ed.), *Plant Responses to Elevated CO_2: Evidence from Natural Springs*, vol. Cambridge University Press, Cambridge, 1997.

Raynaud, D., J. Jouzel, J. M. Barnola, J. Chappellaz, R. J. Delmas and C. Lorius, The ice record of greenhouse gases, *Science*, *259*, 926-934, 1993.

Rayner, P. J., I. G. Enting, R. J. Francey and R. Langenfelds, Reconstructing the recent carbon cycle from atmospheric CO_2, $\Delta^{13}C$ and O_2/N_2 observations, *Tellus*, In press, 1998.

Sabine, C. L., R. M. Key, K. M. Johnson, F. J. Millero, A. Poisson, J. L. Sarmiento, D. W. R. Wallace, and C. D. Winn, Anthropogenic CO_2 inventory of the Indian Ocean, *Global Biogeochem. Cycles*, *13*, 179-198, 1999.

Sarmiento, J. L., T. M. C. Hughes, R. J. Stouffer and S. Manabe, Simulated response of the ocean carbon cycle to anthropogenic climate warming, *Nature*, *393*, 245-249, 1998.

Sarmiento, J. L. and C. Le Quéré, Oceanic carbon dioxide uptake in a model of century-scale global warming, *Science*, *274*, 1346-1350, 1996.

Sarmiento, J. L., R. Murnane and C. L. Quéré, Air-Sea CO_2 transfer and the carbon budget of the North Atlantic, *Philosophical Transactions of the Royal Society*, *348*, 211-218, 1995.

Sarmiento, J. L., J. C. Orr and U. Siegenthaler, A perturbation simulation of CO_2 uptake in an ocean general circulation model, *J. Geophys. Res.*, *97*, 3621-3646, 1992.

Sarmiento, J. L.,and E.T. Sundquist,Revised budget for the oceanic uptake of anthropogenic carbon dioxide. *Nature*, *356*, 589-593,1992.

Schimel, D. S.,VEMAP participants,and B.H.Braswell, Spatial variability in ecosystem processes at the continental scale:models,data and the role of disturbance, *Ecol.Monog.*, *67*, 251-271,1997.

Schimel, D., D.Alves,I.Enting,M.Heimann, F. Joos, D. Raynaud and T.Wigley, CO_2 and the Carbon Cycle,in *Climate Change 1995*, vol.edited by J.T. Houghton,L. G. M. Filho,B.A.Callander, N. Harris,A.Kattenberg and K.Maskell, 76-86,Cambridge University Press, Cambridge,1996.

Schimel, D.,I. G. Enting,M.Heimann,T. M.L. Wigley, D. Raynaud, D.Alves and U. Siegenthaler, CO_2 and the Carbon Cycle,in *Climate Change 1994*, vol.edited by J.T. Houghton,L. G. M. Filho, J. Bruce,H.Lee,B.A. Callander, E.Haites, N. Harris and K.Maskell,35-71, Cambridge University Press,Cambridge,1995.

Schroeder, P.,S.Brown, J. M.Mo,R.Birdsey and C. Cieszewski,Biomass estimation for temperate broadleaf forests of the United Staes using inventory data, *Forest Science*, *42*, 424-434,1997.

Smith,S. V. and R. W. Buddemeier, Global change and coral reef ecosystems, *Ann.Rev. Ecol.Syst.*, *23*, 89-118,1992.

Stallard,R. F.,Terrestrial sedimentation and the carbon cycle: Coupling weathering and erosion to carbon burial, *Global Biogeochem.Cycles*, *12*, 231-258,1998.

Stauffer, B.,T. Blunier,A.Dallenback,A.Indermuhle, J. Schwander,T. F. Stocker, J.Tschumi, J. Chappellaz, D. Raynaud,C. U. Hammer and H.B.Clausen,Atmospheric CO_2 concentration and millennial-scale climate change during the last glacial period, *Nature*, *392*, 59-62,1998.

Stauffer, B.,E.Lochbronner, H.Oeschger and J. Schwander, Methane concentration in the glacial atmosphere was only half that of the preindustrial Holocene, *Nature*, *332*, 812-814,1988.

Stephens,B.B.,R. F. Keeling,M.Heimann,K. D. Six,R. Murnane and K.Caldeira,Testing global ocean carbon cycle models using mesurements of atmospheric O_2 and CO_2 concentrations, *Global Biogeochem.Cycles*, *12*, 213-230,1998.

Takahashi,T.,R.A. Feely, R. F. Weiss,R.H. Wanninkhof, D.W. Chipman,S.C.Sutherland and T.T.Takahashi,Global air-sea flux of CO_2: An estimate based on measurements of sea-air pCO_2 difference, *Proc. Natl.Acad.Sci.*, *94*, 8992-8299,1997.

Takahashi,T. R.,R.H. Wanninkhof, R.A. Feely, R. F. Weiss, D. W. Chipman, N. Bates, J. Olafsson,C.Sabine, and S. C. Sutherland, Net sea-air CO_2 flux over the global oceans: An improved estimate based on the sea-air pCO_2 difference.In: *The proceedings of the 2nd CO_2 in the Oceans Symposium*,Tsukuba, Japan, January 18-23, 1999.

Tans, P. P., P. S.Bakwin and D.W. Guenther,A feasible global carbon cycle observing system:a plan to decipher today's carbon cycle based on observations, *Global Change Biology*, *2*, 309-318,1996.

Tans, P. P., J.A.Berry and R. F. Keeling,Oceanic $^{13}C/^{12}C$ Observations: A new Window on Ocean CO_2 Uptake, *Global Biogeochem.Cycles*, *7*, 353-368,1993.

Tans, P. P.,I. Y. Fung and T.Takahashi,Observational constraints on the global atmospheric CO_2 budget, *Science*, *247*, 1431-1438,1990.

Taylor, N. K.Seasonal uptake of anthropogenic CO_2 in an ocean general circulation model, *Tellus*, *47B*, 145-169, 1995.

Toggweiler, J. R.,K.Dixon,and K.Bryan,Simulation of radiocarbon in a coarse-resolution world ocean model, 1.Steady state pre-bomb distributions, *J. Geophys.Res.*, *94*, 8217-8242,1989.

Torn,M.S.,S.E.Trumbore, O.A.Chadwick, P. M.Vitousek and D. M.Hendricks,Mineral control of soil organic carbon storage and turnover, *Nature*, *389*, 170-173,1997.

Turner, D. P., G. J. Koerper, M.E.Harmon and J. J. Lee,A carbon budget for forests of the coterminous United States, *Ecol. Appl.*, *5*, 421-436,1995.

Wallace, D.W. R.,Monitoring global ocean inventories, OOSDP Background Rep.5,Ocean Observ. Syst.Dev. Panel,Texas A&M Univ.,1995.

Wanninkhof, R.,Relationship between wind speed and gas exchange over the ocean, *J. Geophys.Res.*, *97*, 7373-7383,1992.

Winn,C. D., F.T. Mackenzie,C. J. Carillo,C.L.Sabine and D. M.Karl,Air-sea carbon dioxide exchange in the North Pacific Subtropical Gyre: Implications for the global carbon budget, *Global Biogeochem.Cycles*, *8*, 157-164, 1994.

Wofsy, S.C.,M.L.Goulden, J. M.Munger, S.M. Fan, P. S. Bakwin et al.,Net Exchange of CO_2 in a mid-Latitude Forest, *Science*, *260*, 1314-1317,1993.

Woodwell, G. M,R.H.Whittaker,W.A.Reiners, G. E.Likens, C.C.Delwiche,and D. B.Botkin,The biota and the world carbon budget, *Science*, *199*, 141-146,1978.

Zhang, J. R.and P. D. Quay,The total organic carbon export rate based on C-13 and C-13 of DIC budgets in the equaotrial Pacific region, *Deep-Sea Research Part II*, *44*, 2163-2190,1997

Acronyms and Abbreviations

ARS	Agricultural Research Service (USDA)
BOREAS	BOReal Ecosystem-Atmosphere Study
BR	Bowen Ratio/Energy Balance (flux measurement towers)
CCSP	Carbon Cycle Science Plan
CFCs	chlorofluorocarbons
CLIVAR	Climate Variability and Predictability Programme (WCRP)
DIC	dissolved inorganic carbon
DOE	Department of Energy
DOM	dissolved organic matter
FAO	Food and Agriculture Organization
FIA	Forest Inventory Analysis (program of the U.S. Forest Service)
ENSO	El Niño–Southern Oscillation
GAIM	Global Analysis,Interpretation and Modelling (IGBP program)
GCOS	Global Climate Observing System
GCTE	Global Change and Terrestrial Ecosystems (IGBP program)
GEOSECS	Geochemical Ocean Sections program
GEWEX/GCIP	Global Energy and Water Cycle Experiment/Continental Scale International Project (World Climate Research Program project)
GOOS	Global Ocean Observing System
Gt C/yr	Billions of metric tons (or “gigatons”) of carbon per year
GTOS	Global Terrestrial Observing System
IGAC	International Global Atmospheric Chemistry Program
IGBP	International Geosphere–Biosphere Program
IPCC	Intergovernmental Panel on Climate Change
JGOFS	Joint Global Ocean Flux Study (IGBP program)
LTER	Long-Term Ecological Research (study sites maintained by the National Science Foundation)
MERIS	Medium Resolution Imaging Spectrometer
MODIS	Moderate-Resolution Imaging Spectroradiometer
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration
NBP	net biome production
NEP	net ecosystem production
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSF	National Science Foundation
POM	Particulate organic matter
TOC	total organic carbon
TOGA	Tropical Ocean–Global Atmosphere Program
TRANSCOM	Atmospheric transport model comparison study (GAIM project)
USDA	U.S.Department of Agriculture
USGCRP	U.S.Global Change Research Program
VEMAP	Vegetation/Ecosystem Modeling and Analysis Project
WCRP	World Climate Research Programme
WOCE	World Ocean Circulation Experiment (WCRP program)