A U.S. CARBON CYCLE SCIENCE PLAN

**A Report of the
Carbon and Climate Working Group
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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.

[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 inter-annual/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 manage ment 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.**