5 | Global Carbon Cycle

Strategic Research Questions

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

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

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

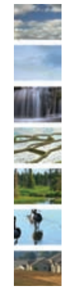
7.4 How do global terrestrial, oceanic, and atmospheric carbon sources and sinks change on seasonal to centennial time scales, and how can this knowledge be integrated to quantify and explain annual global carbon budgets?

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

7.6 How will the Earth system, and its different components, respond to various options for managing carbon in the environment, and what scientific information is needed for evaluating these options?

See Chapter 7 of the *Strategic Plan for the U.S. Climate Change Science Program* for detailed discussion of these research questions.

Over the past two centuries, fossil-fuel emissions, land-use changes, and other human activities have contributed to atmospheric carbon dioxide (CO_2) and methane (CH_4) concentrations that are unprecedented over the past 650,000 years. Future atmospheric concentrations of these gases will depend on fossil-fuel emissions; uptake, storage, and



U.S. GLOBAL CARBON CYCLE SCIENCE PROGRAM

The U.S. Global Carbon Cycle Science Program contributes to all CCSP Goals, focusing particularly on Goal 2: *Improved quantification of the forces bringing about changes in the Earth's climate and related systems*. It directly addresses the global carbon cycle research elements and questions (*CCSP Strategic Plan*, Chapter 7) and is synergistic with the ecosystems, global water cycle, climate variability and change, atmospheric composition, land-use and land-cover change, human contributions and responses, and observations research elements.

release of carbon by Earth's ecosystems; biogeochemical gradients between major carbon reservoirs; and active management activities. Options available to societies for stabilizing or mitigating greenhouse gases in the atmosphere through management of carbon in the environment include reduction of carbon emissions at the source and/or sequestration of carbon through biospheric or geospheric storage and engineered approaches.

In FY 2007, the U.S. Global Carbon Cycle Science Program will continue to address the magnitude and variability of the carbon reservoirs of the North American continent and adjacent ocean basins, and transfers of carbon between the Earth's ecosystems, by characterizing and quantifying the biological, chemical, and physical processes that determine carbon cycling dynamics. Integrating observations, measurements, and models of the atmospheric, terrestrial, and oceanic components of the carbon cycle is the essential core research effort needed to quantify multi-scale carbon budgets, develop successful carbon management strategies, and reduce the uncertainties in carbon cycle dynamics. Through research efforts such as the North American Carbon Program (NACP) and the Ocean Carbon and Climate Change (OCCC) Program, the U.S. Global Carbon Cycle Science Program will continue to provide critical science information on the fate of carbon in the environment and how cycling of carbon may change or be managed in the future. By integrating models, observations, measurements, and experimental results at multiple spatial and temporal scales, we will be better able to quantify carbon budgets, develop successful carbon management strategies,

THE NORTH AMERICAN CARBON PROGRAM

Designed to address strategic research question 7.1, NACP will quantify the magnitudes and distributions of terrestrial, freshwater, oceanic, and atmospheric carbon sources and sinks for North America and adjacent oceans; understand the processes controlling source and sink dynamics; and produce consistent analyses of North America's carbon budget that explain regional and continental contributions and year-to-year variability. NACP is committed to reducing uncertainties related to the buildup of CO_2 and CH_4 in the atmosphere and the amount of carbon, including the fraction of fossil-fuel carbon, being taken up by North America's ecosystems and adjacent oceans.

and reduce the uncertainties about the carbon cycle and changes in atmospheric concentrations of CO_2 and CH_4.

THE OCEAN CARBON AND CLIMATE CHANGE PROGRAM

Designed to address strategic research question 7.2, OCCC will focus on oceanic monitoring and research aimed at determining how much atmospheric CO_2 is being taken up by the ocean at present and how climate change will affect the future behavior of the oceanic carbon sink. NACP and OCCC are synergistic, converging in addressing carbon dynamics in the coastal oceans adjacent to North America and at its land-sea margins, where changes in the terrestrial system greatly influence carbon processes in the coastal ocean.

Activities planned for FY 2007 will focus on integrating observational capabilities, completing monitoring networks that measure carbon fluxes and changes in stocks, conducting manipulative experiments in North America and adjacent oceans, and modeling the carbon cycle for diagnostic and predictive analyses. This integrative approach will include quantification of landscape-scale carbon dynamics, intensive terrestrial measurement campaigns and experimental studies, atmospheric monitoring networks, global ocean carbon survey and inventory, coastal ocean and atmospheric carbon exchange measurements, and model comparisons.

Successful completion of this work will yield, and be measured by, integrated and accessible observational databases; peer-reviewed publications on quantification of carbon budget components and multi-scale carbon cycle processes; more accurate estimates of changes occurring or likely to occur in carbon cycle-related systems; reduced uncertainty in U.S. carbon source and sink estimates; and a stronger scientific basis for developing technical and policy options for managing carbon.

The agencies responsible for CCSP carbon cycle research (DOE, NASA, NIST, NOAA, NSF, USDA, and USGS) have organized a coordinated, interagency, multidisciplinary research strategy to bring together the infrastructure, resources, and expertise essential for providing this information, reducing uncertainties, and producing integrated carbon budget analyses. A developing dialog with stakeholders, including resource managers, policymakers, and other decisionmakers, has been established and will be maintained to ensure that the information provided is effective.

HIGHLIGHTS OF RECENT RESEARCH

The following are selected highlights from the participating CCSP agencies that support a multitude of land, ocean, atmosphere, and remote-sensing projects on the carbon cycle. These science highlights describe progress contributing to the goals of the *CCSP Strategic Plan*.

Synthesis, Analysis, and Modeling

Cumulative Carbon Dioxide Emissions.[8] Global emissions from fossil-fuel consumption and cement manufacture reached an all-time high of approximately 7 billion metric tons of carbon in 2002. Since 1751, over 297 billion metric tons of carbon have been released to the atmosphere from human use of fossil fuels and cement production, with half these emissions occurring since 1978. Globally, consumption of crude oil and coal account for almost 77% of fossil-fuel CO_2 emissions. Combustion

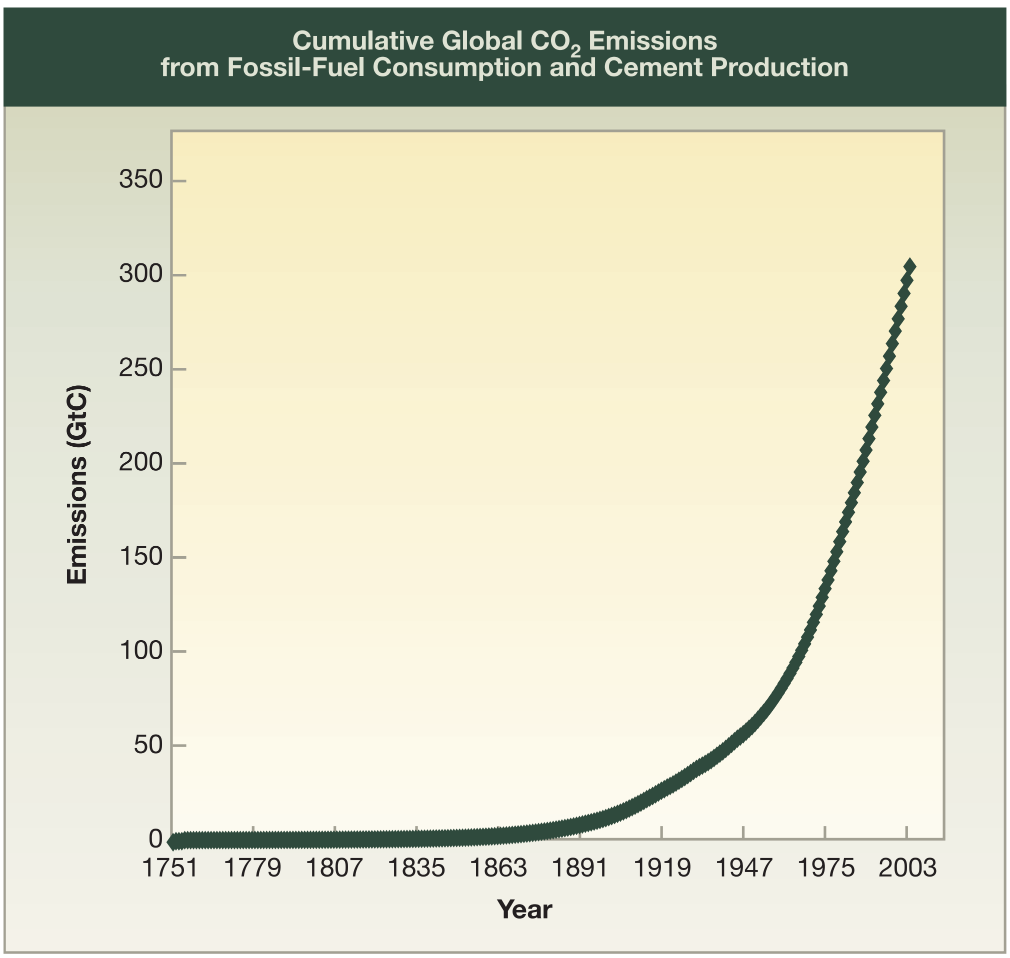
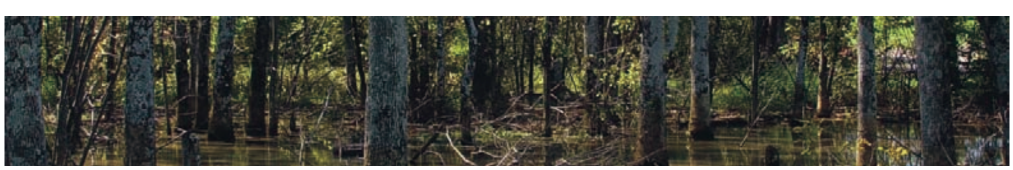


Figure 28: Cumulative Global CO_2 Emissions from Fossil-Fuel Consumption and Cement Production. This chart provides cumulative global fossil-fuel CO_2 emissions from 1751 to 2003. *Credit: T.A. Boden, DOE/Oak Ridge National Laboratory.*

of gas fuels (e.g., natural gas) accounted for 19.3% (1.4 billion metric tons of carbon) of the 2002 total, which reflects a gradually increasing global utilization of natural gas. Releases during cement production have doubled since the mid-1970s and now contribute about 0.25 billion metric tons of carbon per year globally. Twenty nations generate roughly 80% of global fossil-fuel CO_2 emissions (see Figure 28).

Modeling the Carbon Cycle in a Changing Climate.[5] Simulations were conducted over the period 1820-2100 using the National Center for Atmospheric Research (NCAR) Community Climate System Model fully coupled to a land carbon cycle model and an ocean carbon cycle model with marine biology and carbonate chemistry (NCAR carbon-CSM1.4). The simulations show decreases in both terrestrial and oceanic uptake of fossil-fuel CO_2 as rates of fossil-fuel emissions rise and greenhouse gas increases affect global climate. Such changes in carbon sinks in turn affect climate through their influences on atmospheric CO_2 and its radiative forcing and thus represent an important feedback within the coupled carbon cycle and climate systems. Warming affects air-sea exchange, oceanic circulation, and ocean biology. Compared to simulations with constant CO_2 radiative forcing, in 2100 the fully coupled model forced by "business-as-usual" fossil-fuel emissions has 1.2 K higher globally averaged sea surface temperature, 17% slower North Atlantic overturning, and 5% lower global efflux of CO_2. These effects lead to approximately 20 Gt (1 Gt = 10^9 metric tons) less total carbon in the oceans in the fully coupled simulations. On land, the fully coupled simulation has less net carbon uptake in the tropics and greater uptake at high latitudes than with constant CO_2 radiative forcing. These regional differences approximately offset each other such that there is only about 20 Gt difference between total terrestrial carbon sinks in the two simulation experiments. Overall, climate-carbon feedbacks within the NCAR carbon-CSM1.4 model are similar to those in other models (e.g., the Hadley Centre model), albeit with weaker sensitivity. In the NCAR model, the climate sensitivity to a doubling of atmospheric CO_2 is lower than for other models. As a result, warming and drying are not as severe and have less impact on photosynthesis and plant mortality in the tropics. Finally, turnover times of terrestrial carbon pools affect the longevity and magnitude of land sinks, and the more rapid turnover of terrestrial carbon in NCAR carbon-CSM1.4, validated by the simulation of the contemporary atmospheric CO_2 cycle, leads to a weaker sink on land with less sensitivity to climate (see Figure 29).



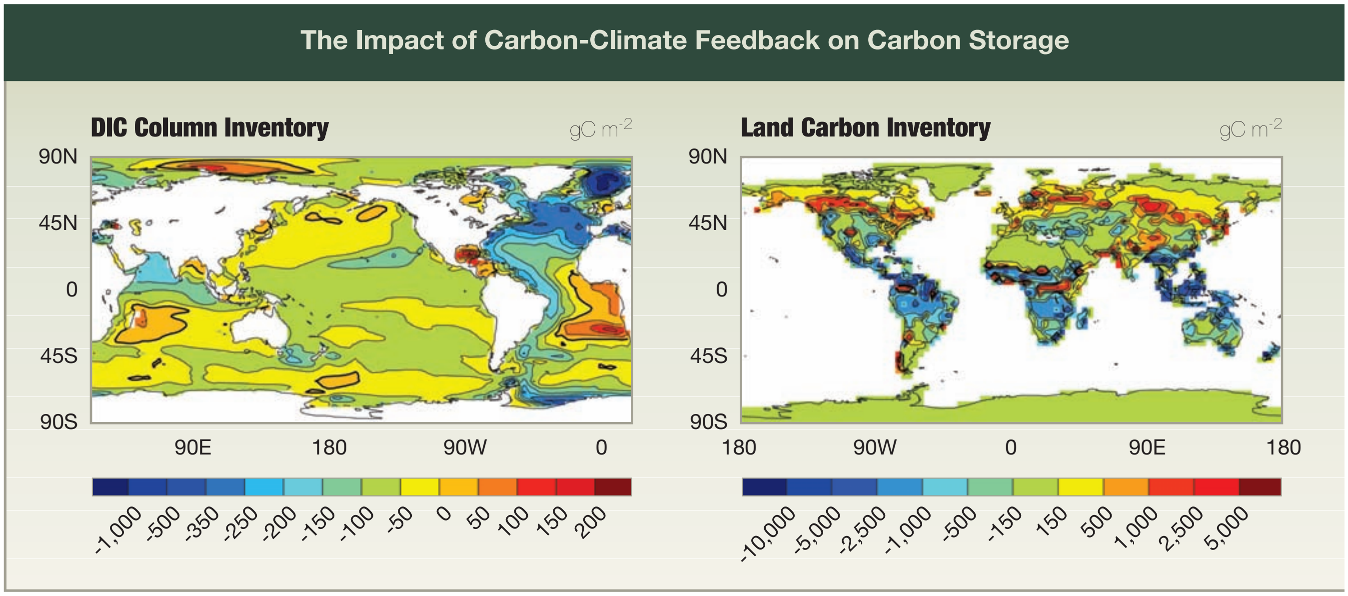


Figure 29: The Impact of Carbon-Climate Feedback on Carbon Storage. These products illustrate the impact of carbon-climate feedback on carbon storage in oceanic (left panel) and terrestrial (right panel) systems. Units are grams carbon m^{-2}; DIC = dissolved inorganic carbon. *Credit: I.Y. Fung, University of California; S. C. Doney, Woods Hole Oceanographic Institution; K. Lindsay, National Center for Atmospheric Research; and J. John, University of California (reproduced from* **Proceedings of the National Academy of Sciences** *with permission from the National Academy of Sciences).*

Influence of Land-Cover Change on the Carbon Cycle.[24] Land-surface processes influence the atmospheric carbon budget, with implications for the dynamics of Earth's climate system, ecosystem sustainability, and human well-being. Land-use changes such as forest cutting and regrowth, urbanization, and the development, abandonment, and management of agricultural land can all affect how much carbon is stored in plants and the soil. Merged data sets have been used to analyze and quantify the rates and causes of land-use and land-cover change for more than 3,000 study areas across the Nation. The land-use changes are used as inputs to models of the carbon cycle, resulting in maps of areas that remove CO_2 from or release CO_2 to the atmosphere. The results show that forest regions of the southeastern United States have been removing CO_2 from the atmosphere, but at a decreasing rate. In the northwestern Great Plains between 1972 and 2001, the modeling indicated that soil carbon stocks increased by nearly 4 metric tons per hectare. The carbon dynamics of other regions are being investigated as the land-cover change data become available. When complete, the influence of land-cover change on carbon dynamics from the 1970s to the present will be mapped for the conterminous United States. The research integrates many data sources to understand how land management affects atmospheric concentrations of greenhouse gases, and thus contributes to climate change (see Figure 30).

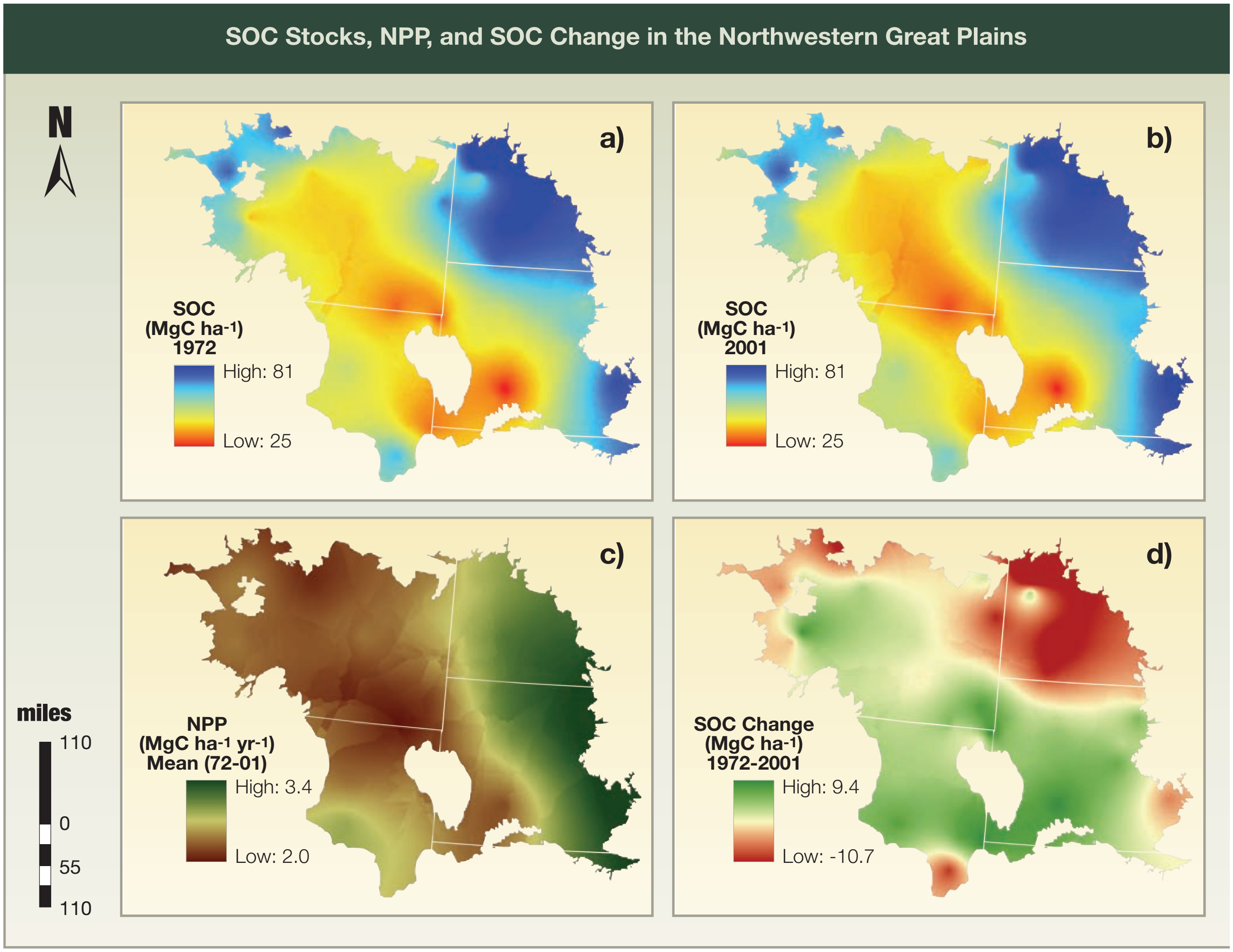


Figure 30: SOC Stocks, NPP, and SOC Change in the Northwestern Great Plains. These products provide spatial distribution patterns of soil organic carbon (SOC) stocks, net primary production (NPP), and SOC change in the northwestern Great Plains (portions of Montana, Nebraska, North Dakota, South Dakota, and Wyoming) between 1972 and 2001: (a,b) the spatial distributions of total SOC stocks in 1972 and 2001, respectively; (c) the annual average NPP between 1972 and 2001; and (d) the change in SOC stocks from 1972 to 2001, with positive values indicating an increase in SOC stocks over this period. *Credit: Z. Tan, South Dakota Center for Biocomplexity Studies; S. Liu, SAIC; C.A. Johnston, South Dakota Center for Biocomplexity Studies; T.R. Loveland, U.S. Geological Survey; L.L. Tieszen, U.S. Geological Survey; J. Liu, U.S. Geological Survey; and R. Kurtz, U.S. Geological Survey (reproduced from* ***Global Biogeochemical Cycles*** *with permission from the American Geophysical Union).*

Global Modeling Estimates of Ocean Carbon Production.[2] Researchers compared 24 models that estimate depth-integrated primary production from satellite measurements of ocean color and seven models that use general circulation models coupled with ecosystem or biogeochemical models. The model results varied the most for the Southern Ocean, sea surface temperature under 10°C, and chlorophyll concentration exceeding 1 mg m^{-3}. Based on the conditions under which the model results varied the most, researchers concluded that current models based on ocean color are challenged by high nutrient-low chlorophyll conditions and extreme temperatures or chlorophyll concentrations. Although current models are very useful, further progress in primary production modeling requires improvements in understanding the effect of temperature on photosynthesis and in parameterizing the maximum photosynthetic rate.

Carbon Exchange between Terrestrial Ecosystems and the Atmosphere

Isolating the Effect of Vegetation on Net Ecosystem Carbon Exchange.[15,23] The Ameriflux network, established in 1996, provides continuous observations of ecosystem level exchanges of CO_2, water vapor, energy, and momentum spanning diurnal, synoptic, seasonal, and interannual time scales. Researchers isolated the effect of vegetation on net ecosystem exchange of CO_2 by observing carbon fluxes in adjacent AmeriFlux sites within each of three vegetation types representing the main successional stages in the uplands of the southeast United States. Contrary to expectations, researchers found that the mean annual net ecosystem exchange in the mature forest was not lower than that of the fast-growing plantation. Year-to-year variation in water availability showed that the pine plantation was better equipped than the broadleaf forest to profit from peak wet periods but was also more susceptible to drought. Preliminary scaling of the three-site data to a 100-km^2 area demonstrates the effect of water availability on the average net ecosystem exchange. Net ecosystem exchange of the plantation stands increased 33% in a wet year and decreased by 21% in a dry year.

Carbon Losses from High-Elevation Mountain Forests.[10,11,20] Scientists used a model-data synthesis approach to extract process-level information from multiple years of eddy covariance measurements of net ecosystem exchange of CO_2 at an AmeriFlux subalpine forest ecosystem. They found that photosynthesis, and possibly leaf respiration, are down-regulated when the soil is frozen, and the metabolic

processes of soil microbes vary in the summer and winter because of the existence of distinct microbial communities. Soil respiration was observed to be exceptionally sensitive to small changes in beneath-snow soil temperature, meaning that small changes in snow amount can cause large changes in the amount of CO_2 lost from

Figure 31: The Niwot Ridge Ameriflux Site, Colorado. Studies of soil carbon fluxes beneath the snowpack of the Niwot Ridge Ameriflux site have shown that recent declines in the snowpack of the western United States are likely to affect the flux of CO_2 from the soil to the atmosphere. This research illustrates the tight coupling between the water and carbon biogeochemical cycles in mountain ecosystems. *Credit: S. Burns, National Center for Atmospheric Research.*

mountain forest ecosystems. Using DNA sequence analyses and studies of microbial growth kinetics, the researchers showed that the high sensitivity of soil CO_2 loss to changes in snow depth, and concomitant change in soil temperature, is caused by a uniquely adapted soil microbial community that exhibits exponential growth and high rates of substrate utilization at the cold temperatures that exist beneath the snow (see Figure 31).

Soil Respiration in Ecosystem Carbon Balance.[19] Researchers reviewed the role of soil respiration in determining ecosystem carbon balance, and the conceptual basis for measuring and modeling soil respiration, a significant component of ecosystem respiration. Because autotrophic and heterotrophic activity belowground is controlled by substrate availability, soil respiration is strongly linked to plant metabolism, photosynthesis, and litter fall. This link dominates both base rates and short-term fluctuations in soil respiration and suggests many roles for soil respiration as an indicator of ecosystem metabolism. However, the strong links between above- and below-ground processes complicate the use of soil respiration to understand changes in ecosystem carbon storage. Root and associated mycorrhizal respiration account for roughly half of soil respiration, with much of the remainder derived from decomposition of recently produced root and leaf litter. Changes in the carbon stored in the soil generally contribute little to soil respiration, but these changes, together with shifts in plant carbon allocation, determine ecosystem carbon storage belowground and its exchange with the atmosphere.

Elevated CO_2 Concentration Increases Terrestrial Photosynthesis and Productivity.[6,14] Free-Air CO_2 Enrichment (FACE) research technology creates a platform for multidisciplinary, ecosystem-scale research on the effects of elevated atmospheric CO_2 concentrations over extended periods. FACE experiments are providing unique information on the productivity and carbon processes of ecosystems, and the results are being used in prognostic models to evaluate ecosystem responses to rising atmospheric CO_2 concentration and climate change. Most field experiments are carried out at approximately 550 parts per million (ppm) of CO_2, which is roughly 170 ppm above the ambient concentration (380 ppm). An analysis on the net primary productivity (above- and below-ground) response in four FACE experiments in forest stands found that the response to CO_2 is highly conserved across a broad range of productivity, with a median increase in production of 23 ± 2%. Belowground, meta-analysis of 35 experimental observations from diverse temperate ecosystems indicated that CO_2 enrichment increased soil carbon by an average of 5.6% over 2 to 9 years. Researchers also directly measured similar increases in soil carbon in two experiments where the vegetation responded to CO_2 enrichment with large increases in the production of root litter. Over half of the accrued carbon was protected by incorporation into microaggregates. These findings indicate that the carbon storage capacities of many soils, including some with large organic matter stocks, may not be saturated at present and might be capable of serving as carbon sinks if detrital inputs increase as a result of passive CO_2 fertilization or active management efforts to sequester carbon. The surprising consistency of responses across diverse sites provides a benchmark for predicting ecosystem response, and research can now focus on unresolved questions about carbon partitioning and retention, and spatial variation in the response of net primary productivity caused by availability of other growth-limiting resources.

Regulation of Carbon Sequestration under Elevated Atmospheric Carbon Dioxide.[3,4,7] Researchers have made substantial progress in past years toward understanding nitrogen regulation of carbon sequestration. For example, it was found that spatial variability in soil nutrients, primarily nitrogen, had a dominant impact on how fast the canopy of pines developed after seedlings were planted. Areas where nitrogen was limiting had a less-developed pine canopy and slower carbon sequestration by the pine. Higher atmospheric CO_2 concentration increased canopy leaf area and carbon sequestration, with the increase being proportionally smaller where nitrogen was limiting. The immobilization of nitrogen in woody biomass depletes soils of mineralizable nitrogen, leading to progressive nitrogen limitation of net primary productivity at elevated CO_2 levels. In a metadata analysis of the literature on nitrogen limitation of ecosystem carbon sequestration, it was found that at elevated CO_2 concentrations, significant increases in averaged carbon and nitrogen contents occurred in the plant, litter, and soil pools, leading to more net carbon and nitrogen accumulations in ecosystems. The analysis suggests that complete down-regulation of CO_2 stimulation of plant growth and carbon sequestration is not pervasive across ecosystems and that net nitrogen accumulation probably supports long-term carbon sequestration in response to rising atmospheric CO_2 concentration. Researchers also noted that belowground microbes showed a shift in activity from the decomposition of labile carbon substrates to more recalcitrant carbon substrates, indicating a decline in labile carbon inputs to the soil under elevated CO_2 and progressive nitrogen limitation.

Impact of Land Use on Carbon Sources and Sinks

Carbon Sequestration across Forested Ecosystems.[17] A cross-site vegetation and land-use analysis of eight forested sites from Ontario, Canada, to Mississippi shows that ecosystem carbon sequestration averaged 2.5 metric tons per hectare per year. Carbon sequestration in soils, on the other hand, averaged 10 to 30% of this value, with some notable losses. The use of system-wide averages rather than site-specific data would therefore produce very significant errors. Future predictions and management scenarios will require that site-specific controls be used to model changes in landscape carbon dynamics. Calcium and nitrogen availability were major controls of carbon dynamics, suggesting the possibility of improvements in the management of forested systems.

Carbon Budget Effects of Selective Logging in Tropical Forests.[1] Remote sensing has been used to quantify tropical deforestation and make substantial reductions in uncertainties concerning the contribution of tropical land-use change to the global carbon budget. However, uncertainties remained regarding the effects of selective logging, previously considered undetectable in satellite imagery. Selective logging is the cutting of a limited number of marketable trees, with logs transported off-site. U.S.-sponsored investigations within the international Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) applied new spectral unmixing methods, developed using the EO-1 Hyperion satellite sensor, to Landsat imagery for the top five timber-producing states of the Brazilian Amazon. The development of a robust library of forest spectral signatures using Hyperion observations and the use of pattern-recognition techniques customized for logging patterns in Brazil enabled detailed discrimination of selective logging in an almost fully automated process. The researchers combined their logging results with field-based forest-canopy gap-fraction and roundwood-extraction data to calculate the total wood-extraction rates and carbon losses. Total carbon losses

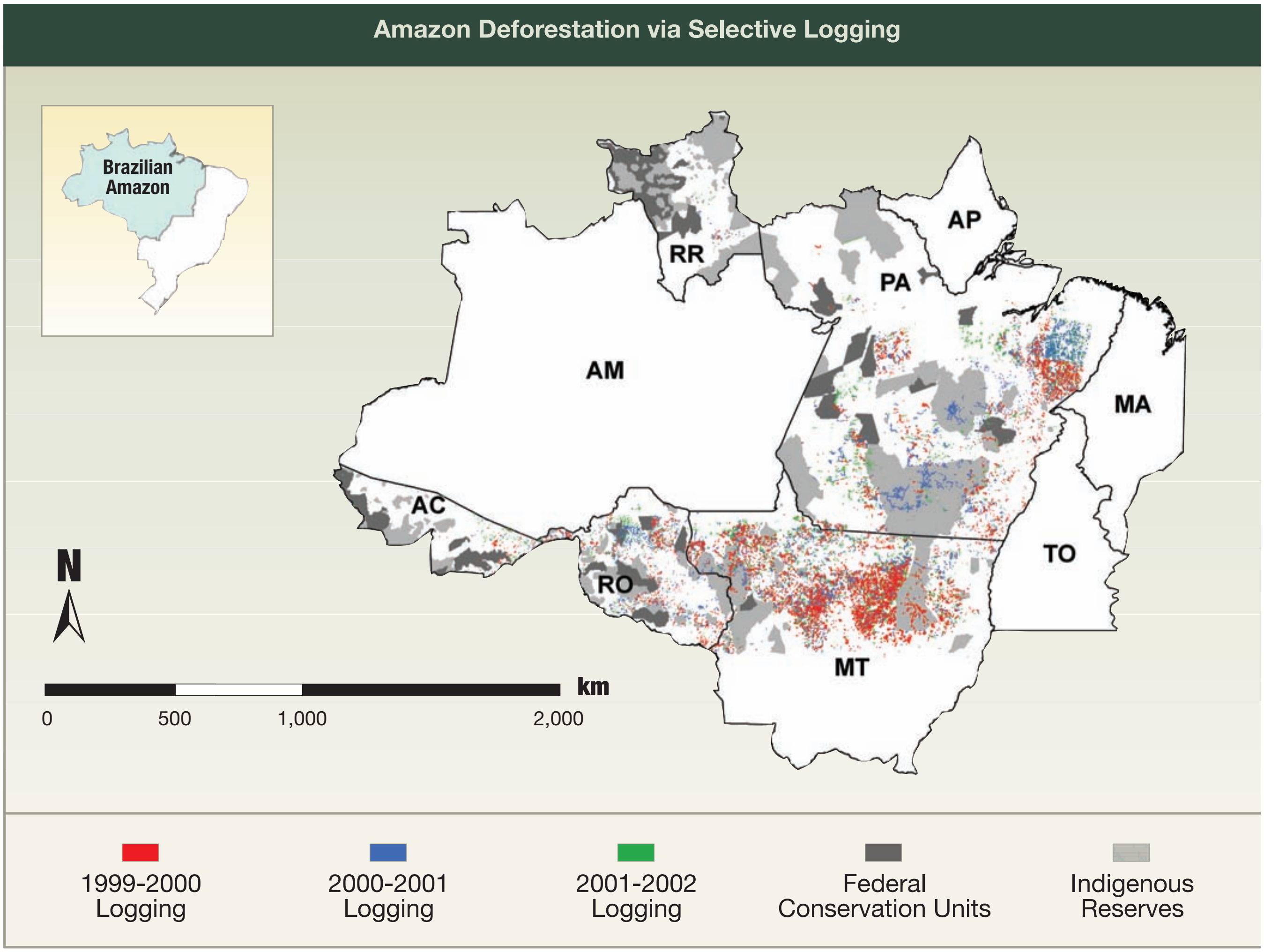


Figure 32: Amazon Deforestation via Selective Logging. Remote sensing has measured Amazon deforestation for three decades, but selective logging has been mostly invisible to satellites. A new large-scale, high-resolution, automated remote-sensing analysis of selective logging was conducted for the top five timber producing states of the Brazilian Amazon. Logged areas ranged from 12,075 to 19,823 $km^2\ yr^{-1}$ (±14%) between 1999 and 2002, equivalent to 60 to120% of previously reported deforested area. In 2000, 2001, and 2002, roundwood production averaged 49.8, 29.8, and 26.6 million m^3, respectively. The total volume harvested equaled 10 to 15 MtC. In addition to roundwood, residual stumps, branches, foliage, and roots are left to decompose in the forest, subsequently returning to the atmosphere as CO_2 over approximately a decade. Each year 27 to 50 million m^3 of wood were extracted, and a gross carbon flux of about 0.1 Gt was destined for release to the atmosphere as a result of logging. *Credit: G.P. Asner, Carnegie Institution of Washington; D.E. Knapp, Carnegie Institution of Washington; E.N. Broadbent, Carnegie Institution of Washington; P.J.C. Oliveira, Carnegie Institution of Washington; M. Keller, University of New Hampshire; and J.N. Silva, Empresa Brasileira de Pesquisa Agropecuária-Amazonia Oriental (reproduced with permission from* ***Science****).*

were approximately 8 metric tons per hectare contained in roundwood and 34 to 50 metric tons per hectare associated with fine and coarse debris. Integrated to the regional scale, this represents a gross loss of carbon from the forest of about 0.1 Gt for each year of logging. This value increases the estimated gross annual anthropogenic loss of carbon from Amazonian forests by up to 25% over carbon losses from deforestation alone (see Figure 32).

Deforestation Monitoring for Decision Support in Brazil.[12] In a related study, data products developed by LBA researchers using observations from the Moderate Resolution Imaging Spectroradiometers (MODIS) on the Terra and Aqua satellites are being used in Brazil to conduct near-real-time monitoring of deforestation to alert government authorities and the public to unknown and sometimes illegal locations of forest clearing. One system, called DETER, focuses on the legal Amazon; another called SAID also includes the woodlands and savannas to its south. This information is being used by regulatory agencies in Brazil for rapid response and by private conservation organizations interested in the prevention and control of deforestation.

Effects of Fire Behavior and Burn Severity on Carbon Emissions in Boreal Forests.[9] Wildfire is a major disturbance in boreal ecosystems, and changing climate has great potential to alter fire behavior, fuel consumption, and the resultant emissions to the atmosphere. Research on seven experimental prescribed fires on dry Scotch pine (*Pinus sylvestris*) sites in central Siberia showed a large range in fuel consumption and carbon emissions (4.8 to 15.4 metric tons of carbon per hectare) in surface fires, indicating the variability of burning conditions and fire behavior, and a loss of 18 to 23 metric tons of carbon per hectare in crown fires. Currently, fires in these pine forests are dominated by relatively frequent (30 to 50 years), low-severity surface fires. Any increase in the annual area burned by high-severity surface fires or crown fires due to changing climate will affect both short-term carbon storage and fire-related emissions of CO_2 and other greenhouse gases (see Figure 33).

Figure 33: Variations in Surface Fire Intensity in Boreal Scotch Pine Forests. Variations in surface fire intensity cause a wide range of fuel-consumption, fire emissions, and ecosystem fire effects. *Credit: S.G. Conard, U.S. Department of Agriculture Forest Service.*

Ocean Carbon Processes

Impact of Carbon Dioxide Changes on Biological Processes in Adjacent Ocean Basins.[16] An international team of researchers assessed the impacts of changes in ocean chemistry driven by atmospheric CO_2 on ocean biology, particularly carbonate-based biology, in the context of a changing climate or increasingly acidic global ocean. Model simulations indicate that future emissions of CO_2 could cause an increase in ocean acidity by the end of this century. This would affect many biological organisms that require carbonate to build their hard outer shells, a major biological carbon sink in the ocean. Thus a chemical shift in the carbonate system to a more acidic equilibrium would change the growth rate and pattern of the affected organisms, or dissolve the carbonate component of their shells, which would likely lead to death. Corals within reef structures are among the carbonate organisms most likely to be affected. Coral reefs are critical for marine fisheries, providing habitat and nursery grounds.

Fate of Carbon Particles in the Ocean.[18] Sinking particulate matter, such as diatom shells and zooplankton excretions, is the major process for exporting carbon from the sea surface to the ocean interior. During its transit toward the sea floor, most particulate organic carbon (>90%) is returned to inorganic form and redistributed in the water column. The ability to predict quantitatively and mechanistically the depth profile of remineralization is critical for predicting the response of the global carbon cycle to environmental change. Novel techniques are now being used to investigate the depth profile of mineralization, with the unexpected finding that average sinking velocity changes little with depth between 200 and 1800 m, despite the decrease in percent particulate organic carbon. If these observations can be generalized, they signify that through aggregation and disaggregation processes, particle size and sinking velocity adjust to changes in particle density, always yielding the same sinking velocity spectrum. This suggests that remineralization time is directly proportional to depth in remineralization profiles and enables calculation of absolute rates.

Global Continental Margins are Significant Carbon Sinks.[13] Current models of ocean carbon cycling generally stop at the continental shelf break, with little or no exchange between the ocean and the continental margins. Using satellite data to compute annual global net primary production between 1998 and 2001, researchers derived the global particulate organic carbon flux settling below the permanent thermocline and to the seafloor using an empirical model of particulate organic carbon remineralization. Although the margins accounted for 40% of the particulate organic carbon flux from the thermocline, the shallower depth of the marginal seas means that a larger fraction is buried in shelf sediments and a smaller fraction is recycled to CO_2.

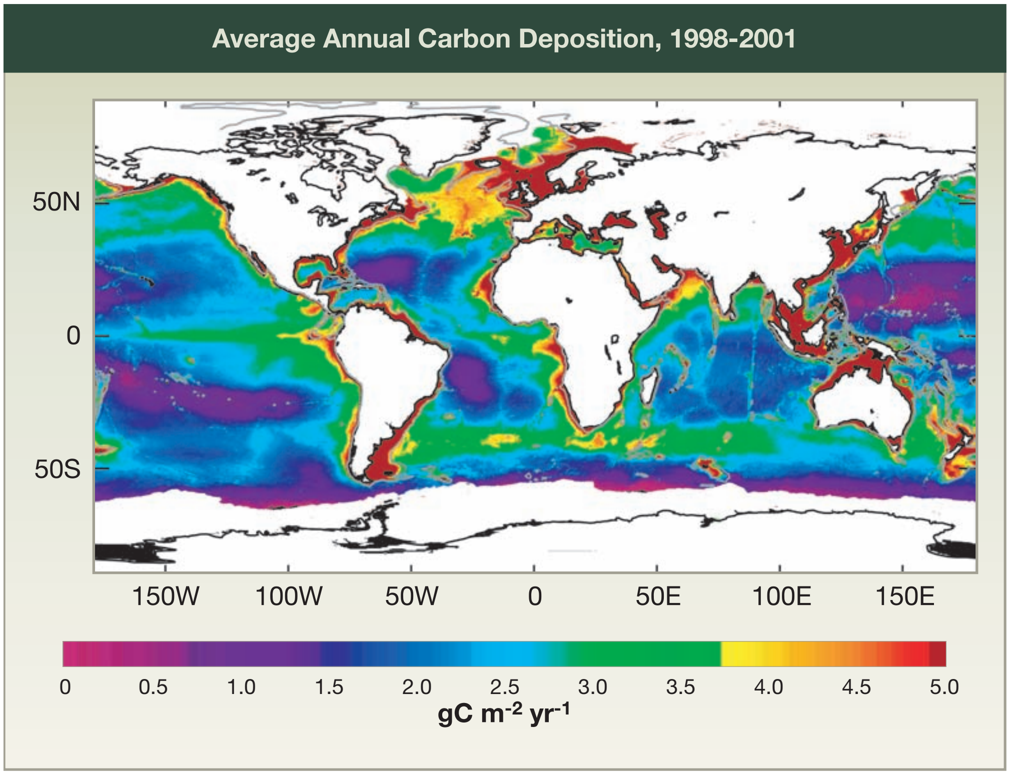
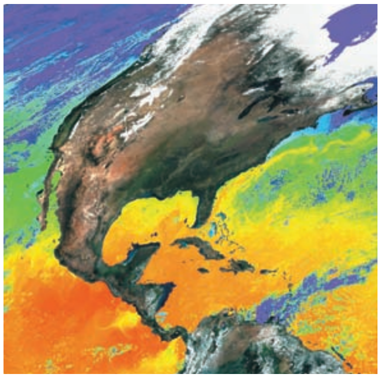


Figure 34: Average Annual Carbon Deposition, 1998-2001. This product estimates average annual particulate organic carbon flux (in gC m^{-2} yr^{-1}) deposited on the ocean bottom between 1998 and 2001, with continental margins outlined in white at the 2,000-m depth contour. *Credit: F.E. Muller-Karger, University of South Florida; R. Varela, Estación de Investigaciones Marinas de Margarita; R. Thunell, University of South Carolina; R. Luerssen, University of South Florida; C. Hu, University of South Florida; and J.J. Walsh, University of South Florida (reproduced from* **Geophysical Research Letters** *with permission from the American Geophysical Union).*

Approximately 67% of the total ocean flux to the sediments occurs over the continental margins, and at least 0.06 Gt of carbon per year (about 40% of the ocean flux) may be buried on continental margins. These regions must be accounted for in realistic models of the global carbon cycle and its linkages to climate change (see Figure 34).

Changes in Dissolved Organic Carbon Export to the Ocean by Arctic Rivers.[22] Climate warming is having a dramatic effect on the vegetation distribution and carbon cycling of terrestrial subarctic and Arctic ecosystems. Researchers presented hydrologic evidence that warming is also affecting the export of dissolved organic carbon and bicarbonate at the large-basin scale. In the Yukon River Basin, flow-adjusted dissolved organic carbon export significantly decreased during the growing season from 1978-1980 to 2001-2003, indicating a major shift in the transfer of carbon from terrestrial to aquatic systems. Researchers concluded that decreased dissolved organic carbon export, relative to total summer and autumn water discharge, results from an increased flow path from soil to surface waters, longer residence times, and microbial mineralization of dissolved organic carbon in the soil active layer and groundwater aquifer. Counter to other predictions, researchers argued that continued warming could result in decreased dissolved organic carbon export to the Bering Sea and Arctic Ocean by major subarctic and Arctic rivers due to increased respiration of organic carbon on land.



Characterization of Carbon Matter in Coastal Ocean Ecosystems.[21] Different algorithms are used with data from satellite-based sensors to retrieve ocean-based properties. One critical ocean property for ecological and biogeochemical research is the carbon-based biomass of primary producers, or biomass from phytoplankton chlorophyll *a*. As shown in Figure 35, two statistically similar phytoplankton chlorophyll *a* algorithms were compared to test how well the two algorithms retrieved the biologically and biogeochemically invaluable phytoplankton biomass property. Data from the comparison of the two algorithms in the global climatology showed that chlorophyll *a* concentrations differ, with the percentage differences approaching 100% at high latitudes. There is a strong relationship between the difference in phytoplankton chlorophyll *a* concentrations and colored dissolved organic material (CDOM) concentrations, indicating that the currently used empirical algorithm overestimates chlorophyll *a* in regions of high CDOM. The bias is caused by the fixed CDOM/chlorophyll *a* relationship in the algorithm, and thus there is an overwhelming need for new satellite technology to better discriminate between chlorophyll *a* and CDOM fractions.

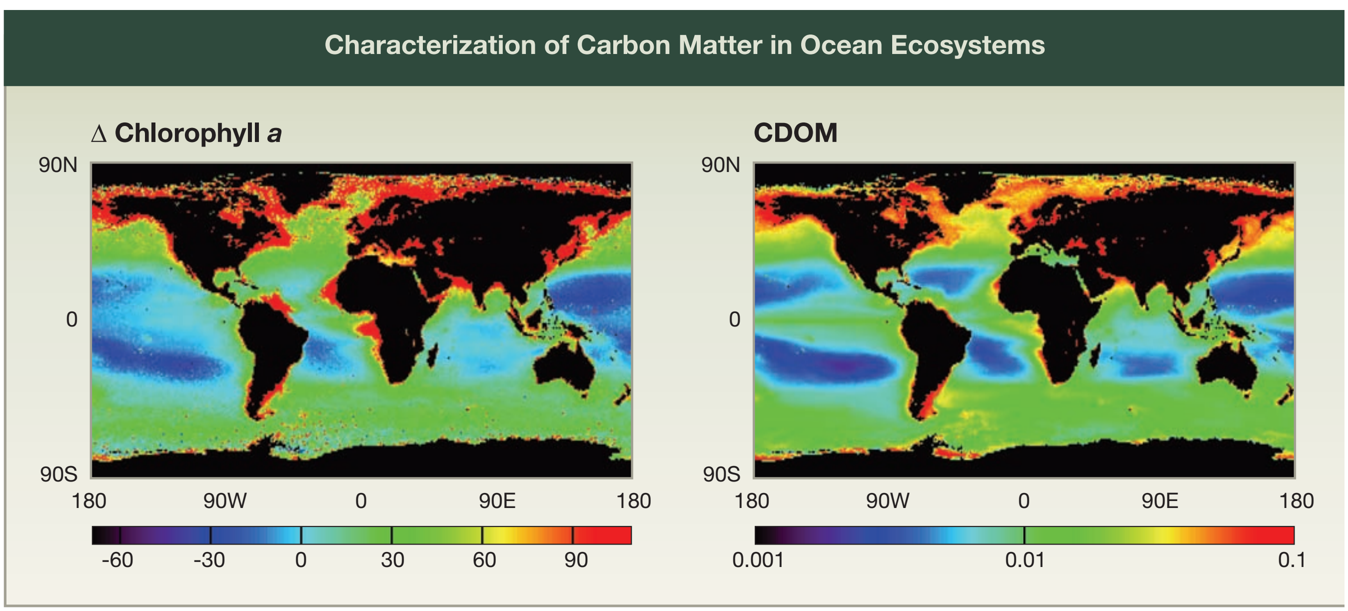


Figure 35: Characterization of Carbon Matter in Ocean Ecosystems. These data compare two algorithms used to infer the global climatology. Chlorophyll *a* concentrations differ, approaching 100% at high latitudes. The right-hand panel shows the global estimate of colored dissolved organic material (CDOM). *Credit: D.A. Siegel, University of California, Santa Barbara; S. Maritorena, University of California, Santa Barbara; N.B. Nelson, University of California, Santa Barbara; M.J. Behrenfeld, Oregon State University; and C.R. McClain NASA/Goddard Space Flight Center (reproduced from* **Geophysical Research Letters** *with permission from the American Geophysical Union).*

Highlights of FY 2007 Plans

In FY 2007, integrating observations, measurements, and models of the atmospheric, terrestrial, and oceanic components of the carbon cycle is the core research needed to quantify carbon budgets at multiple spatial and temporal scales, develop successful carbon management strategies, and reduce the uncertainties in quantifying carbon cycle dynamics. The integrated approach will include quantification of landscape-scale carbon dynamics, intensive terrestrial measurement campaigns and experimental studies, atmospheric monitoring networks, global ocean carbon surveys and inventory, coastal ocean and atmospheric carbon exchange measurements, long-term studies identifying and quantifying phenomena and processes critical to reducing uncertainties and improving predictions of future carbon dynamics, coupled carbon-climate modeling, data assimilation, and model comparisons. In 2007, carbon fluxes will be determined by "top down" (atmospheric composition and inverse transport model) techniques and, for the first time, compared and integrated with "bottom up" (land-based experiments, inventories, and monitoring networks) estimates:

- *Improved Modeling for Projections of Carbon and Climate*. New investments will be made in synthesis and modeling studies to support the NACP, the Mid-Continent NACP Intensive Campaign, the OCCC Program, global carbon dynamics, and climate change assessment activities.
- *Couple Models of the Carbon Cycle and the Climate System*. New studies will be initiated to couple models of the carbon cycle and the climate system and to analyze these models to identify, quantify, and understand process controls and feedbacks within the coupled systems. This next step in carbon cycle research responds directly to the CCSP plan for a 2- to 4-year milestone, product, and payoff of "interactive global climate-carbon cycle models that explore the links and feedbacks between the physical and biogeochemical systems." This research will be conducted in close coordination with the climate variability and change research element.
- *Carbon Data Assimilation*. New research will be conducted to develop, test, and apply carbon data assimilation and data fusion schemes that incorporate *in situ* and remotely sensed data and focus on enabling forecasts of changes in atmospheric CO_2 concentrations at short or long time scales with estimates of uncertainty. Studies to explore assimilation of carbon data from ocean margins into general circulation models will be initiated.

These activities will address Questions 7.1, 7.2, 7.3, and 7.6 of the CCSP Strategic Plan.

Terrestrial Carbon Observations and Monitoring Networks. The following research will continue to address NACP implementation strategies and other carbon cycle science goals:

- *Scaling Carbon Fluxes from Sites to Landscapes to Regions*. Carbon dioxide data from AmeriFlux sites will be extended across landscapes and regions based on turbulent transport theories using land-cover information derived from fine-resolution satellites. Several such studies will focus on landscapes throughout the United States. Some studies will extend these analyses to larger scales combining regional data from the MODIS sensor with measurements from many other AmeriFlux sites. Results from these new studies will be compared to estimates of fluxes based on biogeochemical models and, for some sites, concentration profiles of atmospheric carbon measured using tethered-sonde balloons or aircraft. The latter comparisons will be used to estimate the uncertainties involved in scaling.
- *Regional Carbon Monitoring*. A carbon atmospheric observing system will continue across the Nation in support of research to reduce uncertainty in U.S. carbon sources and sinks. The current system now includes 19 aircraft sites, *in situ* instruments at three tall towers, and seven surface flask sampling sites. The sampling, analysis, and data management activities are complemented with a growing modeling capability to aid in positioning new sites as well as in interpreting the increased flow of data. The global sampling and analytical network will continue as the cornerstone of international efforts to maintain a record of, and understand the global changes in, atmospheric CO_2 concentration and distribution over the past 50 years. The network is a critical component of the Global Climate Observing System. The program will provide critical data for analysis of regional carbon sources and sinks and useful decision-support information for carbon management.
- *Landscape-Scale Carbon Sources and Sinks in Various Ecosystem Types*. An improved observation and monitoring system that integrates several existing programs will continue at several forest sites in the United States. Standardized estimates of carbon stocks and flows will provide a strong scientific foundation for development and deployment of carbon sequestration technology to mitigate greenhouse gas emissions. Enhancing observations at experimental forests has additional benefits such as facilitating use of these sites for carbon management research and demonstration projects, and providing the basis for an "early warning" capability to detect the initial impacts of climate change. On rangelands, the recently developed National Carbon Map will be used to identify and quantify the effects of fire, grazing, and other natural disturbances and human activities on the status and trends of carbon

stocks and fluxes. The results will delineate better the spatial and temporal dimensions of current U.S. carbon sources and sinks.

- *Continental-Scale Satellite Data Time Series*. Continuing investments will be made to improve and temporally extend the continental-scale Earth Observing System satellite data products used for spatial extrapolation of carbon stock and flux estimates. In addition, these data products on primary productivity, land cover, vegetation, and phytoplankton properties of the Earth's lands and oceans will be used to drive carbon and climate models.
- *Carbon and Water Processes in the Earth System*. The Biocomplexity in the Environment initiative will continue to define and quantify key mechanisms, feedbacks, and interactions of the carbon cycle through empirical observations, theory, and modeling at the level of continents, ocean basins, and air masses. In early 2007, researchers will begin addressing carbon processes at a variety of spatial and temporal scales, and address how results can be scaled up for relevance to regional or global scales. Critical feedbacks, couplings, and interactions between the carbon and water cycles will also be addressed.

These activities will address Questions 7.1, 7.2, 7.3, and 7.6 of the CCSP Strategic Plan.

Terrestrial Field Studies: Processes, Synthesis, and Integration. Long-term field experiments and major campaigns will continue to identify processes that are critical to reducing uncertainties in carbon budgets and improving model-based predictions of future terrestrial carbon dynamics. Several scientific syntheses are anticipated in FY 2007:

- *Mid-Continent NACP Intensive Campaign*. An intensive field investigation centered on the mid-continent region of North America will continue to develop and test methods for regional and continental estimates of carbon sources and sinks through 2007. When the field studies are completed, investigators will evaluate and compare two independent approaches for estimating carbon fluxes at the regional scale: the "top down" approach using atmospheric measurements and inverse models, and the "bottom up" approach using vegetation and soil carbon inventories, land cover, meteorological information, and models. This prototype study will integrate existing data on crop, forest, and soil carbon content with data from the AmeriFlux network, airborne sensors, and satellites. Biological process information from current experiments, atmospheric profiling, and statistical databases of the mid-continent region will play key roles in the analysis. Results will contribute to the design of more comprehensive research for quantifying and explaining variation of carbon sources and sinks across North America.
- *Analysis of Regional- and Continental-Scale Carbon Budgets*. NACP studies will continue to focus on using remote-sensing observations, state-of-the-art carbon models, and data assimilation schemes to conduct integrated analysis of regional-

and continental-scale carbon budgets. These studies will bring U.S. capabilities for Earth observation, the remote measurement of biophysical properties, and related modeling, analysis, and data management to bear on NACP and related OCCC objectives.

- *Free-Air CO_2 Enrichment (FACE) Studies*. A synthesis of CO_2 exchange and belowground research at FACE sites will continue to create a data archive of photosynthesis, stomatal conductance, soil carbon and nitrogen pools, surface soil CO_2 efflux, nitrogen cycling, microbial activity, and essential metadata. Integration of field data will occur through modeling of photosynthesis and soil nitrogen cycling. This integration will be used to calibrate prognostic models of ecosystem net primary production under elevated CO_2 in nitrogen-limited and nitrogen-replete systems (i.e., under future scenarios of atmospheric nitrogen deposition).
- *Amazonian Carbon Balance*. A synthesis of carbon dynamics in the Amazon region of South America will be completed, including an assessment of the region's overall role as a source or sink of carbon and a quantification of the associated uncertainties.
- *Carbon and Water Balances in Managed Ecosystems in China and the United States*. The U.S.-China Carbon Consortium (USCCC) was established in 2003 as a collaborative effort between American and Chinese institutions studying the role of managed ecosystems in the global carbon and water cycles. The USCCC is developing a network of eddy-covariance flux towers to measure directly and continuously the net ecosystem exchange of CO_2 and water using standardized data collection, analysis, and reporting methods, and will synthesize results across sites. Planned work will focus on site installation, data protocol standardization, and initial data collection
- *Tracking Permafrost Melting and Associated Release of Biologic and Sequestered Carbon*. Ongoing research on carbon dynamics in Arctic and subarctic landscapes will be enhanced through integration with regional monitoring to assess the sources and sinks of carbon in rapidly thawing permafrost terrain. Carbon movement, including vertical flux to the atmosphere, lateral export to surface waters and the ocean, and descending transport to and re-sequestration in deeper soils, will be assessed in an integrated manner by using the Yukon River Basin and adjacent coastal ocean as a

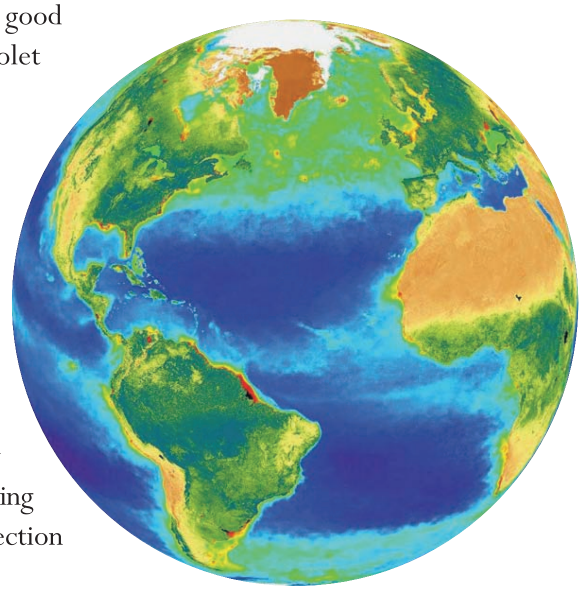
frame of reference. This assessment will begin in 2007 during the initial year of the International Polar Year.

- *Determining Carbon Sequestration Capacity in Wetlands*. Methods for greenhouse gas mitigation through terrestrial carbon sequestration are being developed that will also meet traditional wildlife habitat and ecosystem objectives in bottomland hardwood forests of the Lower Mississippi River Valley and prairie pothole wetlands in North Dakota. Wetland restoration activities will continue to be monitored to quantify the influence of land-use change on greenhouse gas emissions, identify environmental factors controlling carbon emissions and sequestration, and provide recommendations and decision-support tools for maximizing sequestration in ways that are consistent with current options for habitat restoration.

These activities will address Questions 7.1, 7.2, 7.3, 7.4, 7.5, and 7.6 of the CCSP Strategic Plan.

Ocean Carbon and Climate Change Research. New studies will be initiated, and existing studies will be strengthened, to advance the goals of the OCCC implementation strategy:

- *Refine Satellite-Based Global Estimates of Phytoplankton Carbon Biomass*. Phytoplankton biomass, specifically carbon-based estimates within biogeochemical and ecological models, is dependent on resolving CDOM absorption of the ultraviolet part of the spectrum. To accomplish this task, new measurement capabilities for the generally riverine-delivered CDOM will be developed to detect and quantify CDOM from space over a broad spatial area and within a time frame that will support models in development. One problem that will be addressed in the semi-analytical model approach is that atmospheric correction algorithms do not give good retrievals of the important ultraviolet and near-ultraviolet wavebands in coastal regions. To resolve true carbon cycling in not only global but also coastal areas, researchers need new tools in orbit to rigorously separate chlorophyll *a* from CDOM. This will require passive measurements in different wavelength regions as well as new approaches to correcting for absorbing aerosols, perhaps using Light Detection and Ranging (LiDAR) technology.



- *Satellite Data Analysis*. Studies will continue to focus on using ocean color to characterize carbon dynamics globally and on using a variety of satellite and *in situ* data to quantify and understand the spatial variability of air-sea CO_2 flux in the oceans adjacent to North America. Other studies will focus on the development and analysis of remote-sensing data and products that facilitate understanding of the input of non-CO_2, climate-relevant carbon compounds (e.g., dissolved organic matter, carbon monoxide, and CH_4) to the aquatic environment and their fate once there.
- *Dynamics of Carbon Cycling in the Upper Ocean*. The two time-series stations at Hawaii and Bermuda will continue to monitor a suite of critical parameters of the carbon cycle while also supporting a range of carbon-related projects such as nitrogen fixation by unicellular cyanobacteria and phosphorus cycling that determines the amount of carbon fixation. Focused process studies will be completed to better define the role of mesoscale eddies in enhancing new production and the transport of particles from the upper ocean to the deep sea.

- *Ocean Hydrography and Carbon Measurements*. The Repeat Hydrography Program will continue to re-measure key ocean properties along cross-sections in the South Atlantic and North Pacific that were last measured in 1989 and 1991, respectively. The suite of measurements will include conductivity, temperature, depth, oxygen, salinity, nutrients, partial pressure of CO_2, and total carbon.

These activities will address Questions 7.1, 7.2, and 7.4 of the CCSP Strategic Plan.

Development of New Measurement and Analysis Methods. The following activities will be underway to develop new measurement standards and data analysis methodologies for carbon cycle science:

- *Carbon Dioxide Exchange Across the Air-Sea Interface*. New gas sensors will be designed specifically for use on autonomous platforms such as floats, gliders, surface drifters, and autonomous underwater vehicles. The objective is to develop parameterizations for gas exchange rates at high wind speeds, where the largest uncertainties remain for computing net global CO_2 exchange between the ocean and the atmosphere. Modeling and data analysis will focus on understanding the physics of bubble-mediated gas transfer, particularly the processes responsible for gas influx and efflux, the roles of bubble size, and the relationships between wind, waves, bubble generation, ocean turbulence, and vertical exchange.
- *Satellite Measurements of Atmospheric Carbon Dioxide*. Development of the new remote-sensing capabilities of the Orbiting Carbon Observatory (OCO) to measure atmospheric CO_2 will continue. In 2007, the ground data system for OCO will be tested and research will be conducted to prepare for scientific data utilization.

Globally sampled measurements of atmospheric column CO_2 (i.e., the column-integrated CO_2 dry air mole fraction) will provide a hundred-fold increase in the available measurements to drive inverse models and should enable regional resolution of carbon sources and sinks. Launch of the OCO is scheduled for 2008.

- *AmeriFlux Data Assimilation System*. An integrated framework for using AmeriFlux measurements and ecosystem models will continue to improve understanding of terrestrial carbon cycling processes. This framework, called the AmeriFlux Data Assimilation System, takes advantage of diverse, continuous AmeriFlux measurements of CO_2 and energy exchanges, and combines them with a detailed process-based ecosystem model. It will yield information on ecosystem states and carbon sinks in real-time and will be an effective tool for scientists to investigate fundamental ecological processes that are difficult to observe directly.

These activities will address Questions 7.1, 7.2, 7.4, and 7.5 of the CCSP Strategic Plan.

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