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.

The U.S. Carbon Cycle Science Program is making progress in understanding the changes, magnitudes, and distributions of carbon sources and sinks, the processes operating within and between major terrestrial, oceanic, and atmospheric carbon reservoirs, and the underlying mechanisms involved, including human activities, fossil fuel emissions, land use, and climate forcings. Program scientists are currently quantifying many of the intricate complexities and interactions between the major

U.S. CARBON CYCLE SCIENCE PROGRAM

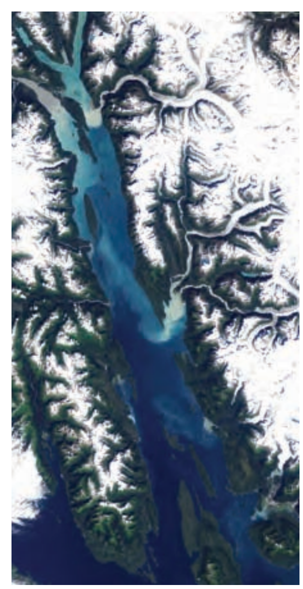
The U.S. Carbon Cycle Science Program contributes to all goals of the *CCSP Strategic Plan* (2003)—focusing particularly on Goal 2, "Improved quantification of the forces bringing about changes in the Earth's climate and related systems." The program addresses directly the six overarching carbon cycle questions of Chapter 7 of the *CCSP Strategic Plan*. The research element is synergistic with the Ecosystems, Global Water Cycle, Climate Variability and Change, Atmospheric Composition, Land-Use and Land-Cover Change, and Human Contributions and Responses research elements. The agencies responsible for carbon cycle research are DOE; NASA; NIST; NOAA; NSF; USDA's Agricultural Research Service (ARS), Cooperative State Research, Education, and Extension Service (CSREES), Forest Service, and Natural Resources Conservation Service (NRCS); and USGS. Together, they have planned and are coordinating a multidisciplinary research strategy to integrate the broad range of needed infrastructure and resources, scientific expertise, and stakeholder input essential for program success and improved decision processes.

carbon reservoirs and climate. To execute this undertaking, Federal agencies and departments with carbon cycle interests coordinate, manage, and support the overall science and implementation plans under two major thrusts: North American Carbon Program (NACP) and Ocean Carbon and Climate Change (OCCC) Program. As these science programs mature and generate needed carbon observations, field and experimental results are being used to constrain advanced carbon models at scales from experimental sites to regions as an important means of incorporating site, regional, and global observations into global carbon models and analyses. The ultimate objective is to develop increasingly realistic and predictive coupled carbon-climate and Earth system models to provide better insight into future feedbacks and drivers between the major components of the Earth system.

In FY 2009, a new CCSP-wide research priority will be initiated to quantify the magnitude and dynamics of carbon cycling of high-latitude ecosystems under abrupt climate change. In support of this research initiative, the U.S. Carbon Cycle Science Program will coordinate a concerted Federal effort addressing high-latitude carbon cycle research (observations, attribution, prediction, and

THE NORTH AMERICAN CARBON PROGRAM

NACP is designed to address strategic research question 7.1, and elements of questions 7.2 through 7.6, in Chapter 7 of the *CCSP Strategic Plan*. For example, it will quantify the magnitudes and distributions of terrestrial, freshwater, oceanic, and atmospheric carbon sources and sinks for North America and adjacent coastal oceans; enhance understanding of 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. This program is committed to reducing uncertainties related to the increase of carbon dioxide and methane 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 coastal oceans.



mitigation), which will be conducted in unison with its priorities under the NACP and OCCC programs. To accomplish the carbon cycle element of the new CCSP priority at high latitudes, the interagency working group will solicit new investments and reprogram previous research investments to complement current research in order to fill gaps, and promote and augment ongoing carbon observations and networks in high-latitude lands and ocean ecosystems. The enhanced emphasis on high-latitude ecosystems will provide critical scientific information on past and current carbon dynamics of undersampled regions of North America and adjacent oceans, as well as other undersampled regions of the world, such as Antarctica and the adjacent Southern Ocean.

THE OCEAN CARBON AND CLIMATE CHANGE PROGRAM

OCCC is designed to address strategic research question 7.2, and elements of questions 7.3 through 7.6, in Chapter 7 of the *CCSP Strategic Plan*. For example, in regards to question 7.2, it will focus on oceanic research aimed at quantifying how much atmospheric carbon dioxide is being taken up by the ocean at the present time and how climate change will affect the future behavior of the oceanic carbon sink. The terrestrial and ocean carbon programs are synergistic, integrating program activities addressing carbon dynamics on the coastal shelves adjacent to North America (questions 7.1 and 7.2), where carbon changes in the terrestrial system greatly influence carbon processes in the coastal ocean.

As research programs mature, scientific and governmental collaborations on carbon cycle science are broadening and escalating with international neighbors within North America as well as with extended Northern Hemisphere interests, international organizations, and global partners.

Highlights of Recent Research

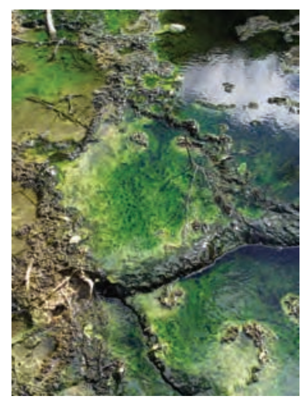
The research highlights that follow are recent selected accomplishments of the U.S. Carbon Cycle Science Program. These accomplishments span carbon cycle issues related to climate forcing factors, terrestrial and oceanic sinks and sources, the atmospheric reservoir, global carbon analysis, carbon management, and other relevant biogeochemical exchanges between the major Earth reservoirs that link to climate.

Climate Forcing

Carbon dioxide (CO_2) and methane (CH_4) are significant forcing agents of climate, and their atmospheric concentrations have been increasing over the past 2 centuries, attributed primarily to human activities. Approximately 85 to 90% of present-day anthropogenic emissions are attributed to fossil fuel combustion, with land-use change accounting for most of the rest. Future concentrations of CO_2 and CH_4 in the atmosphere will depend on the long-term trends in terrestrial and oceanic reservoirs, the rate of exchange between Earth reservoirs, the variability in natural and anthropogenic emissions, and the capacity of natural and managed sinks.

Factors Affecting Fossil Fuel Emissions.[1] An analysis was completed of factors that influence the magnitude, regional patterns, and temporal trends of global emissions of CO_2 from fossil fuels, which dominate climate change forcing. The analysis included demographic, economic, and technological drivers of fossil fuel emissions by using annual time-series data on national emissions, population, energy consumption, and gross domestic product (GDP). Fossil fuel CO_2 emissions can be represented as the product of four driving factors: global population, per capita world GDP, energy intensity of world GDP, and carbon intensity of energy. Results show that growth of global CO_2 emissions since 2000 was driven by a cessation or reversal of earlier declining trends in the energy intensity of GDP and the carbon intensity of energy, coupled with continuing increases in population and per capita GDP. Nearly constant or slightly increasing trends in the carbon intensity of energy have recently been observed in both developed and developing regions.

Terrestrial Carbon Cycle



The terrestrial carbon and water cycles comprise a complex set of interactive biogeochemical processes that transfer carbon between land, oceans, and the atmosphere. Collectively, these processes influence atmospheric CO_2 and CH_4 concentrations. Improving the scientific understanding of the role of these reservoirs and processes in the carbon cycle reduces uncertainty about the factors influencing greenhouse gas increases and provides a stronger foundation for climate change decision support, in particular for carbon management to mitigate CO_2 and CH_4 increases in the atmosphere.

Northern Hemisphere Terrestrial Carbon Sink Analysis.[2,3] Temperate and boreal forests in the Northern Hemisphere act as a substantial carbon sink of 0.6 to 0.7 GtC yr^{-1}, yet recent results from the AmeriFlux research network show that forest disturbance from harvest and fire are responsible for much of the overall variability in forest carbon sequestration. Forests are a carbon source to the atmosphere for as many as 20 years after these events, followed by a long period of carbon sequestration. Using results from observation networks in the United States and Europe, a recently completed Northern Hemisphere synthesis of net ecosystem exchange of CO_2 from differently aged forests found that

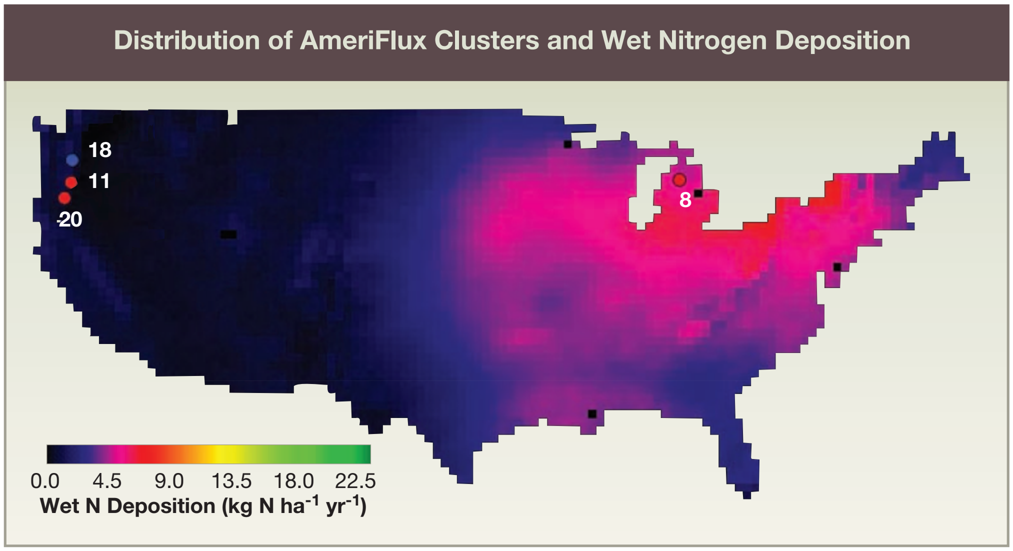


Figure 12: Distribution of AmeriFlux Clusters and Wet Nitrogen Deposition. Distribution of AmeriFlux sites (clusters) and wet nitrogen deposition across the United States used in the Northern Hemisphere analysis of the effects of nitrogen deposition on carbon sequestration by temperate and boreal forests. *Credit: F. Magnani, University of Bologna, (reproduced from* **Nature** *with permission*).

forest age, as a function of stand-replacing disturbances, accounted for approximately 90% of the total variability in net carbon sequestration. The average net carbon uptake over the harvest cycle of the forests was 56% of the maximum observed in mature forests. After accounting for age and disturbance effects (wildfires, harvesting, infestations, etc.), low continuous levels of nitrogen deposition (up to 10 kg N ha^{-1} yr^{-1} wet deposition), largely the result of anthropogenic activities, appear to overwhelmingly account for additional carbon sequestration by these forests (see Figure 12).

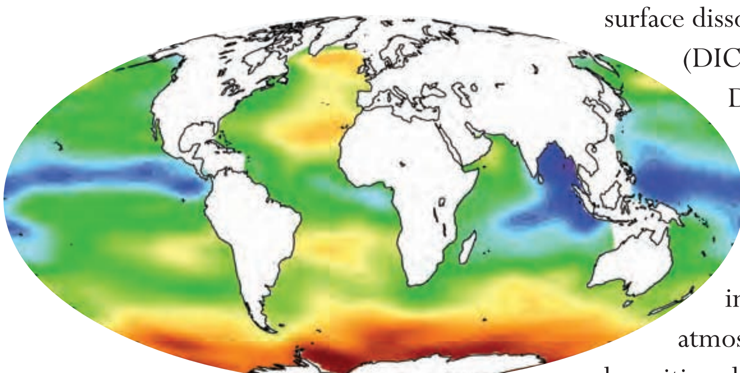
Carbon Distribution between Forest Root and Shoot Systems.[4] One of the largest uncertainties in estimating changes in carbon stocks and understanding the effects of global change on forest carbon sequestration involves carbon allocation to coarse tree roots. Using an approach incorporating successional dynamics in plant communities and whole-tree harvesting including root excavation, a dynamic pattern of root-to-shoot ratios was revealed. Ratios varied from 0.17 for sites with trees less than 5 years old, to 0.80 for a site with 8-year old trees, to 0.29 for a site with 55-year old trees. Determining the causes of this variability in the root-to-shoot biomass allocation through forest maturation requires further research on how these patterns change as functions of growth, environment, and management. Carbon allocation in forest systems has important implications for projecting belowground net primary production responses to global change in studies of regional and continental carbon fluxes.

Carbon and Nitrogen Cycles of Terrestrial Ecosystems.[5] One of the most central processes in the global carbon cycle is the breakdown of plant litter—dead leaves, branches, roots—that releases CO_2 to the atmosphere and provides nitrogen in various forms that can support new plant growth. Understanding what controls the rate of breakdown and nitrogen release in different environments is critical for predicting the effects of climate change on the carbon balance of terrestrial ecosystems. The results of a 10-year experiment conducted at 21 sites showed that in all ecosystems except dry grasslands the amount of nitrogen released is controlled by the initial concentration of nitrogen in the litter and the mass remaining. The results were used to produce simple equations to predict nitrogen release. Because nitrogen is intimately involved in controlling both plant growth and litter breakdown, these equations will contribute to better models of the global carbon cycle.

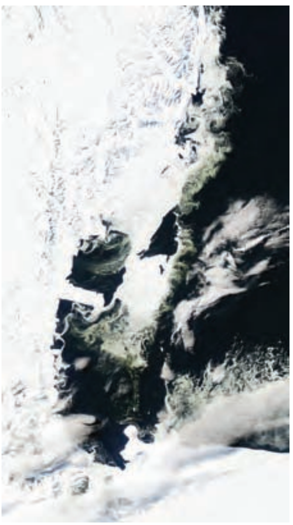
Oceanic Carbon Cycle

The global ocean is a large and important carbon reservoir that regulates the uptake, storage, and release of CO_2, CH_4, and other climate-relevant chemical species to the atmosphere. The future biogeochemical behavior of this reservoir is uncertain because of potential anthropogenic impacts on many ocean processes, in particular the impact of ocean circulation on carbon exchange and the impact of ocean acidification on the physiology, function, and structure of the complex and diverse ocean ecosystem.

Atmospheric Impact on the Ocean Carbon Reservoir.[6,7] The absorption of anthropogenic CO_2 and the deposition of acid rain from fossil fuel and agriculture emissions can both contribute to the acidification of the global ocean, altering surface seawater acidity, and inorganic carbon storage. Researchers have compared these inputs and concluded that (1) acid rain contributes a minor amount (2%) of acidity compared to the ocean uptake of anthropogenic CO_2, although this value likely represents an upper limit, and (2) the decrease in surface alkalinity from acid rain drives a net air-sea release of CO_2, reducing surface dissolved inorganic carbon (DIC). Total alkalinity and DIC changes mostly offset each other, resulting in a small increase in surface acidity. Additional impacts arise from atmospheric nitrogen deposition, leading to elevated



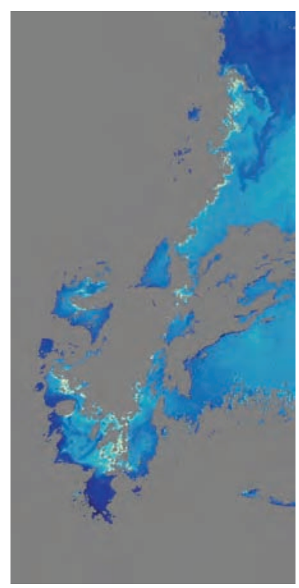
primary production and biological drawdown of DIC that in some places reverses the sign of the surface acidity and air-sea CO_2 exchange. On a global scale, the alterations in surface water chemistry from anthropogenic deposition are a few percent of the acidification, although the impacts are more substantial in coastal waters, where the ecosystem responses to ocean acidification could have the most severe implications for humans.



High-Latitude Systems

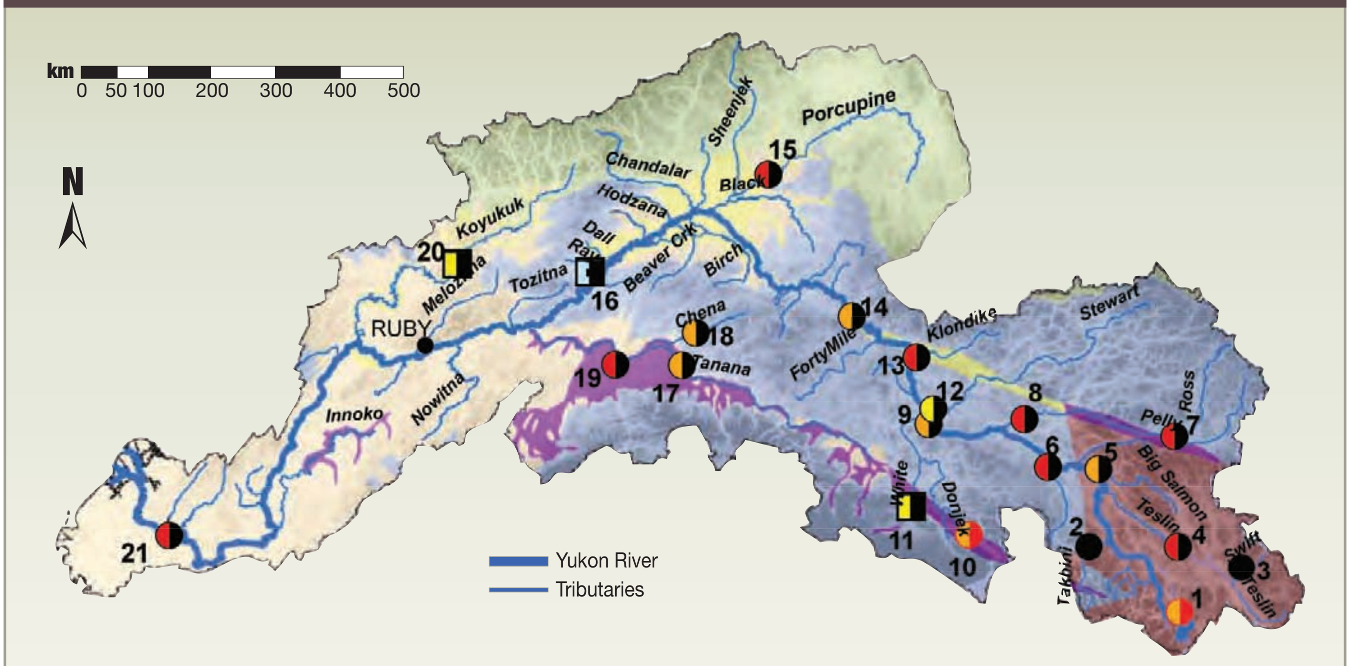
High-latitude systems are becoming increasingly important sources of CO_2 and CH_4 to the atmosphere as regional warming changes ecosystem dynamics in the cold regions. Understanding carbon dynamics in high-latitude systems and the factors that may lead to changes in those dynamics are crucial elements of global carbon modeling and essential for understanding the linkages and feedbacks between carbon reservoirs, ecosystems, land cover, hydrology, and climate variability.

Significance of Marginal Ice Zones.[8] Within the Southern Ocean lie regions where biological dynamics are low, called High Nutrient, Low Chlorophyll (HNLC) regimes. When adjacent to seasonal sea-ice retreat, these marginal ice zones produce relatively high chlorophyll concentrations, indicative of phytoplankton production, extending thousands of kilometers to sea. These high chlorophyll anomalies are extremely variable temporally and spatially because the size and location of the marginal ice zone, defined as areas of recent ice melting and retreat, are highly variable between seasons and years. The production of phytoplankton biomass within this zone is an important food source for higher trophic levels and significantly affects carbon cycling in and across the region. The magnitude and distribution of these regimes with greatly elevated production were unknown prior to the satellite era. Since then the elevated chlorophyll and production associated with these regions have been documented with Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) satellite data for the Southern Ocean, particularly within the marginal ice zone of the Southern Ocean where melting ice stabilizes the water column leading to shallower mixed layers and the release of critical elements, such as iron, to the water column. Both processes lead to production of phytoplankton, which have an unambiguous impact on carbon cycling and eventual export to the deep sea, where it remains sequestered for a very long time.



Permafrost Thaw Releases Additional Carbon and Water to Arctic Streams.[9] Pursuing the hypothesis that permafrost thaw and increased infiltration could potentially increase terrestrial respiration of dissolved organic carbon (DOC) and decrease DOC export, researchers investigated historical stream flow records from the Yukon River Basin in Alaska and Yukon Territory with the goal of isolating and quantifying permafrost thaw and/or glacial and perennial snowpack melt effects on the basin water cycle. The analysis quantified a basin-wide increase in groundwater contribution to streamflow of 0.7 to 0.9% per year, but did not find any compelling evidence for a change in total annual water discharge by the basin's rivers. The Yukon River annually discharges approximately 50 km^3 of groundwater-derived flow to the Bering Sea. The increased groundwater contribution is consistent with the increased infiltration and DOC

Observed Trends in Groundwater Input and Annual Flow • Yukon River



Permafrost Coverage

- Generally Underlain by Continuous Permafrost
- Generally Underlain by Discontinuous Permafrost
- Generally Underlain by Moderately Thick to Thin Permafrost
- Underlain by Discontinuous Permafrost
- Generally Underlain by Numerous Isolated Masses of Permafrost
- Sporadic Masses of Permafrost

Figure 13: Observed Trends in Groundwater Input and Annual Flow • Yukon River. Observed trends in groundwater input (denoted by left side of symbol) and annual flow (denoted by right side of symbol) at Yukon River Basin streamflow stations. Circles and squares indicate flow records longer and shorter than 35 years, respectively. Symbol color scheme indicates statistical significance of Mann-Kendall trend analysis: red = very highly significant ($P<0.01$) increasing trend, orange = highly significant ($0.01<P<0.05$) increasing trend, yellow = moderately significant ($0.05<P<0.1$) increasing trend, light blue = moderately significant ($0.05<P<0.1$) decreasing trend. *Credit: M.A. Walvoord and R.G. Striegl, USGS (reproduced from* **Geophysical Research Letters** *with permission from the American Geophysical Union).*

consumption hypothesis and supports load calculations that indicate a downward trend in the relationship between water and carbon export by the Yukon River during summer and autumn (see Figure 13).

Wildfire Disturbances in High-Latitude Terrestrial Ecosystems.[10,11,12] Wildfire is a common occurrence in northern high-latitude ecosystems, and the ecosystem changes have consequences for carbon feedback to the climate system. Researchers, using a process-based terrestrial ecosystem model, assessed the influence of increases in atmospheric CO_2, climate variability and change, and change in fire disturbance on the exchange of CO_2 and CH_4 in high-latitude terrestrial ecosystems. Using historical fire records through 2002, model analysis indicates that fire played a central role in interannual- and decadal-scale variation of carbon source and sink relationships of northern ecosystems and also suggests that increases in atmospheric CO_2 may be important to consider in addition to changes in climate and fire disturbance. Model projections for northern terrestrial ecosystems indicate that these ecosystems could lose up to 50 GtC over the next 100 years and that net CH_4 emissions could double by the end of the 21st century. These studies suggest that carbon storage in northern terrestrial ecosystems is vulnerable to projected changes in climate and fire disturbance.

Global Carbon Analysis

Ocean phytoplankton and land plants are presently absorbing about half the carbon emissions that humans produce. However, recent global carbon analyses indicate that Earth's reservoirs are becoming less efficient at absorbing fossil fuel emissions and losing their ability to take up additional CO_2.

Carbon Cycle Feedbacks to Climate.[13] How carbon cycle dynamics will change with climate and feed back to atmospheric CO_2 concentration is not fully understood. Increases in plant growing season length are hypothesized as contributing factors to the current observed terrestrial carbon sink. An analysis of growing season variation of CO_2 exchange for a range of vegetation sites, from evergreen and deciduous forests to crop to grasslands and including both cool-season and warm-season vegetation types, found that while the growing season length affected how much CO_2 could be potentially assimilated by a plant community over the course of a growing season, other factors such as nutrient and water availability were also important at this scale. This implies

that the climate warming-induced increase in growing season length may have a limited enhancement effect on terrestrial carbon uptake.

Amazon Forests May be More Resilient than Predicted.[14] Coupled carbon-climate models predict substantial carbon loss from tropical ecosystems and drought-induced collapse of the Amazon forest. These models include a physiological feedback mechanism whereby transpiration is reduced in response to initial drought, which in turn exacerbates the drought by interrupting the supply of transpired water that would otherwise contribute to "recycled" precipitation that supports forest growth. Satellite observations of intact Amazon forests subjected to a widespread and severe drought in 2005 show that the response of the forest is actually to green up, which is indicative of increased transpiration and carbon uptake. Apparently, these deep-rooted forests are responding to the increased availability of sunlight and not to water limitations. These observations suggest that intact Amazon forests may be more resilient than some current models assume, at least to short-term climatic anomalies. Future studies are needed to address forest responses to longer term drought in order to better understand the conditions under which water limitations may actually trigger reductions in carbon uptake (see Figure 14).

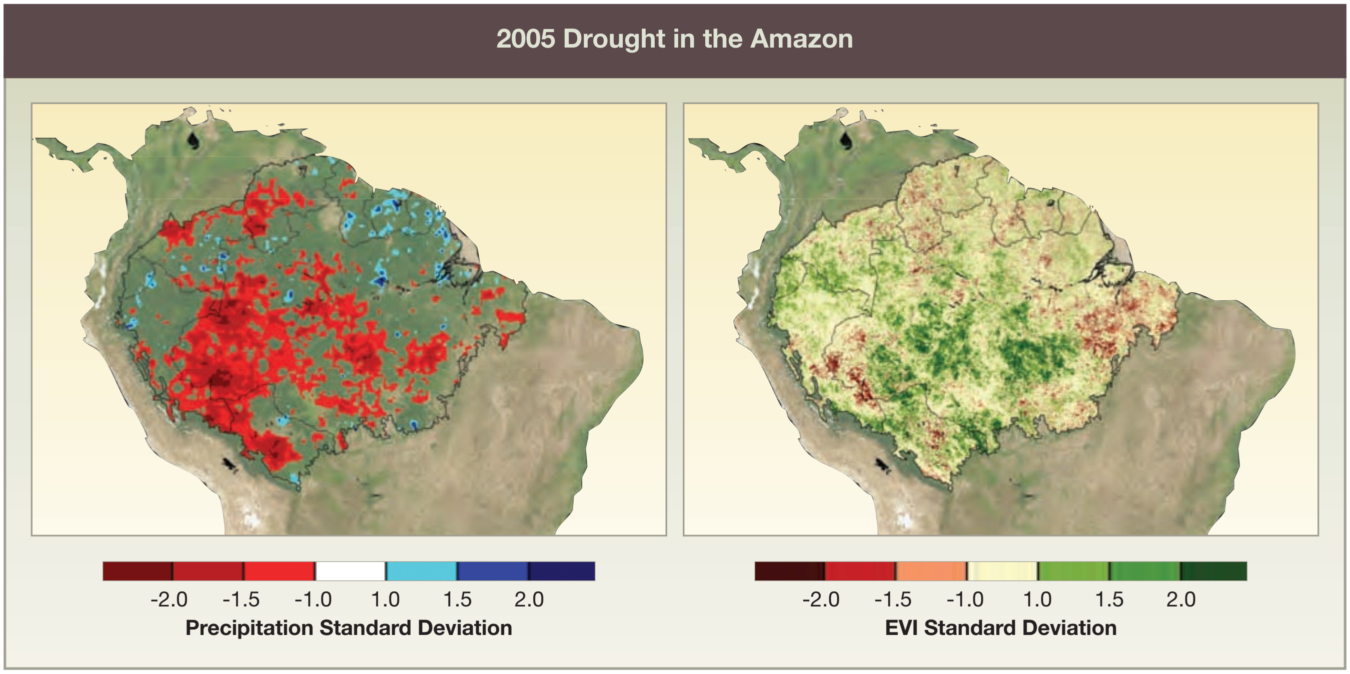


Figure 14: 2005 Drought in the Amazon. During the 2005 drought in the Amazon, intact primary forest showed an increase in photosynthetic activity (right image) despite below-average rainfall (left image). Data from NASA's Terra satellite (right) showed areas of higher (green) and lower (red) growth during the peak of the drought (July-September). Data from the Tropical Rainfall Measuring Mission satellite (left) showed areas of severe rainfall reduction due to the drought (yellow to red) and few areas with above normal rainfall (green to blue). *Credit: K. Didan, University of Arizona*.

Carbon Management and Decision Support

Carbon cycle research provides scientific information to policy and resource decisions about carbon management and mitigation of climate change. The research supported by the carbon cycle program is informing agricultural and resource managers on sequestration, alternative fuels, and inventories, as described in the highlights below. The impact of this research on management strategies is expected to increase over the course of this program.

Soil Carbon Sequestration in Agricultural Lands.[15,16] Based on *in situ* soil carbon concentrations, crop growth characteristics, tillage practices, land-use classification using satellite imagery, and climate variables, a geographic information system (GIS)-based Environmental Policy Integrated Climate (EPIC) model projected the amounts of soil carbon sequestered for an agricultural region in sub-Saharan Africa (Mali). Under contemporary ridge-tillage management practices, year-to-year crop variations were attributed primarily to rainfall, the amount of plant-available water, and the amount of fertilizer applied. Under conventional cultivation, with minimal fertilization and no crop residue management, topsoil was continuously lost due to erosion. The model projections suggest that soil erosion is controlled and soil carbon sequestration is enhanced with a ridge-tillage system because of increased water infiltration. The combination of modeling with land-use classification was used to calculate that about 54 kg C ha^{-1} yr^{-1} (5.4 g C m^{2} yr^{-1}) may be sequestered in the study area with ridge tillage, increased application of fertilizers, and residue management. The EPIC model is now incorporated in a web-based decision-support system for soil carbon management.

Biofuels from Prairie Grasses.[17] The search for alternatives to fossil fuels has attracted attention to biofuels (fuels derived from plants) and especially to corn as a source of ethanol. A study in Minnesota showed that mixtures of native prairie plants, grown on degraded land, may be a better source of biofuel than corn ethanol or soybean biodiesel. Prairie vegetation yields 51% more energy per hectare than is obtained in ethanol from corn grown on fertile land. The higher net energy gain is due in part to much lower inputs such as cultivation, herbicides, irrigation, and fertilizer, as well as the use of the entire above-ground plant rather than just the seed. The prairie vegetation also stores more carbon over time in soils than do systems growing annual crops, thus removing CO_2 from the atmosphere. Low-input, high-diversity prairie vegetation grown on degraded lands can serve as an efficient source of energy and does not compete for fertile soils needed for food production.

An Assessment of the North American Carbon Budget.[18] An evaluation of North American carbon sources and sinks was generated as part of CCSP's Synthesis and Assessment

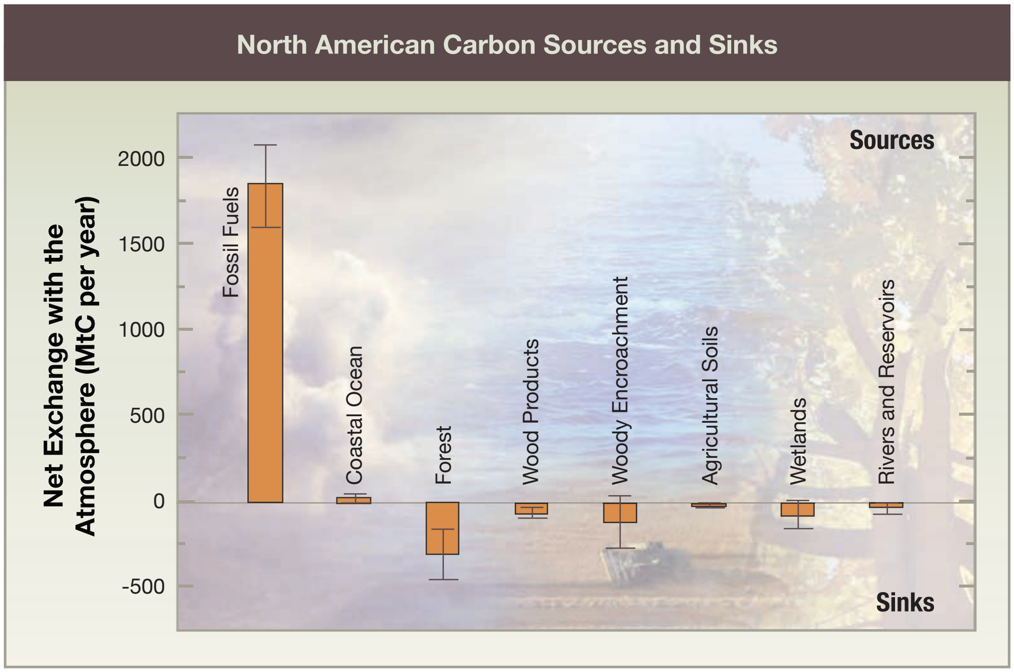
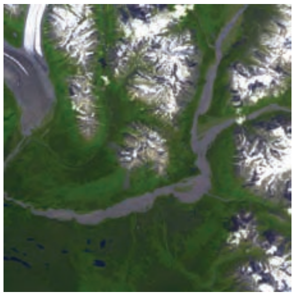


Figure 15: North American Carbon Sources and Sinks. North America is currently a net carbon source (1,336 ± 334 MtC yr^{-1}). A net terrestrial sink of 520 ± 260 MtC yr^{-1} is equivalent to about 30% of fossil fuel emissions in 2003. *Credit: CCSP Synthesis and Assessment Product 2.2.*

Product 2.2, *The First State of the Carbon Cycle Report (SOCCR): North American Carbon Budget and Implications for the Global Carbon Cycle*. The report quantifies North America's fossil fuel emissions for 2003 as 1,856 million metric tons of carbon ±10% (27% of global emissions) and its land sink, primarily in U.S. forests, as 500 million metric tons of carbon ±50% (approximately 30% of North America's emissions). The net release to the atmosphere is 1,350 million metric tons of carbon per year ±25% (see Figure 15). A key finding of the report is that this difference between the sources and sinks is expected to become larger, and that actions to address the imbalance will likely require options that include both emissions reduction and sink enhancement.

North American Carbon Exchange.[19] A CO_2 reanalysis system, CarbonTracker, was used to determine global surface sources and sinks of CO_2. The reanalysis extends from 2000 to 2006 (see <carbontracker.noaa.gov>). Weekly estimates of surface fluxes were produced for 221 land and ocean regions. This advanced data assimilation scheme is focused on relatively well-observed regions, and uses a two-way, nested transport model over North America to simulate circulation at relatively high resolution. The system is capable of handling large amounts of data, and in the most recent analysis over 28,000 individual atmospheric CO_2 observations from the U.S. and Canadian Meteorological Services were assimilated. North American land regions were determined to be a net sink of CO_2, with a mean annual uptake of 0.6 ± 0.4 GtC yr^{-1} and interannual variations of about 0.3 GtC yr^{-1}. This offsets almost one-third of the approximately 1.8 GtC yr^{-1} emissions from fossil fuel burning across North America during the same period.



Highlights of Plans for FY 2009

Enhancing and implementing new carbon cycle studies and observation networks in high-latitude regions of the world along with continuing integration of the NACP and OCCC programs will provide valuable information and improved estimates of the carbon sources and sinks of North American and adjacent coastal systems and ocean basins and their role in the global carbon budget. Data from these observation networks will be assimilated in more comprehensive and advanced regional and global carbon cycle models, coupled carbon-climate models, and integrated Earth system analyses for assessing potential impacts of fossil fuel emissions on terrestrial and ocean ecosystems, land cover and land use, and carbon management strategies. With improved estimates of and greater certainties about the major carbon reservoirs on Earth, scientists will have new insight on how Earth systems functioned under past and present forcings, and predict better how they will respond to future climate forcings.

High-Latitude Carbon Cycle Research. Peatlands (regions of partially decayed vegetation matter) cover a relatively small fraction of the Earth's surface but store nearly one-third of global soil carbon. Climate warming in interior Alaska is already causing some northern peatlands to dry out, while other northern areas are becoming wetter. These changes could have a major effect on the carbon balance of peatlands, including the potential for the release of CO_2 and CH_4, which are important greenhouse gases.

- *Impact of Global Warming* – To determine how climate warming is likely to affect the release of CO_2 and CH_4 from Arctic peatlands, a multi-discipline and -site temperature and water experiment will be implemented in Alaska's high-latitude ecosystems to change soil temperatures, and both increase and decrease the water table depth.
- *Asik Long-Term Study Site* – Ongoing since 1990, research at the Asik watershed, Noatak National Preserve, northwest Alaska, will continue, focusing on quantifying linkages between the topographic (e.g., taiga and tundra areas) declines in snowpack moisture and duration, changes in soil temperature and moisture, release of soil trace gases (CO_2, CH_4, nitrous oxide), and increased export to the aquatic ecosystem of dissolved inorganic nitrogen, DOC, and dissolved organic nitrogen. In FY 2009, a research emphasis will be on linking observations, process studies, and modeling studies from individual watersheds to regional and synoptic scales, and to continue downscaling models to scales appropriate for land management concerns.
- *Improving High-Latitude Carbon Modeling* – Existing models will continue to be used to synthesize and integrate understanding of 20th-century carbon dynamics for high-latitude regions (north of 45°N) across terrestrial, freshwater, and oceanic ecosystems. In FY 2009, these modeling exercises will be advanced with observational and experimental data to improve further the ability to (1) consider the response of carbon currently frozen in peatlands or permafrost soils, and (2) predict how fire

activity and severity will affect carbon storage in northern ecosystems, and in particular the Yukon River Basin.

These activities will address Goals 1, 2, 3, 4, and 5 and Questions 7.1, 7.3, 7.4, and 7.5 of the CCSP Strategic Plan.

North American Carbon Program (NACP). New and reprogrammed investments will be made in observation networks, data management and synthesis, and integrated modeling studies that contribute to NACP goals and objectivities.

- *Terrestrial Carbon Modeling* – Changes in the carbon cycle can lead to changes in the atmospheric CO_2 concentration and thus feed back and force changes in climate and the terrestrial ecosystem carbon cycle. Describing, attributing causes, and predicting future responses requires a process model; an Integrated Terrestrial Carbon Model (ITCM) will be optimally constrained in structure and function by historical and contemporary observations from AmeriFlux and Free Air CO_2 Enrichment (FACE) data to meet this challenge. Regional-scale ITCM simulations will refine CCSP Synthesis and Assessment Product 2.2 sink estimates by resolving geographic fluxes at a finer temporal resolution. Data assimilation for the NACP Mid-Continent Intensive campaign is underway, and regional-scale simulations for the recent historical period will be analyzed to determine causes of seasonal and interannual variations in carbon source and sink strength.

This activity will address Goals 1, 2, 3, 4, and 5 and Questions 7.1, 7.3, 7.4, 7.5, and 7.6 of the CCSP Strategic Plan.

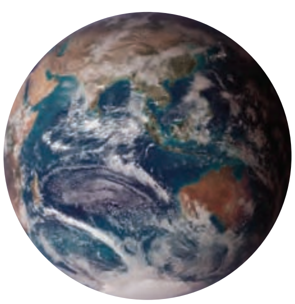
Ocean Carbon and Climate Change (OCCC). New and reprogrammed investments will be made in ocean and coastal carbon observations, synthesis, and modeling studies to support OCCC programs, analyze ocean satellite data, and assess ocean and coastal carbon sinks and sources.

- *Ocean Carbon Observations* – During FY 2009, NSF's Carbon and Water in the Earth System projects—covering regimes spanning the globe, including ocean, coastal, lake, forest, and tundra ecosystems—will expire, while a few ocean and coastal programs will continue beyond FY 2009. New ocean carbon programs will be announced, with submission target dates in FY 2008 and FY 2009, through NSF's Division of Ocean Sciences, NASA's Research Opportunities in Space and Earth Science, and NOAA's Global Carbon Cycling Program. These programs will be supported with reprogrammed investments into a wide range of ocean topics covering carbon cycling, including ocean acidification, terrestrial and coastal carbon exchange, ocean carbon uptake and storage, and related biogeochemical cycles.
- *Large-Scale Coastal Surveys* – Studies are currently underway in the coastal regions of North America to study the incursion and transport of anthropogenic CO_2 and other tracers in coastal ocean waters. This is the first comprehensive effort to measure

partial pressures of CO_2 and related chemical and hydrographic measurements, including DIC, alkalinity, oxygen, nutrients, and CTD (conductivity, temperature, depth), over the entire coastal zone. The survey will establish a baseline describing the geographic distribution of carbon system parameters and develop a set of hydrographic transects with full water column measurements to be revisited over time for studies of interannual changes in physical, chemical, and biological characteristics of the coastal ocean.

- *Ocean Carbon Modeling* – Two key processes are being targeted for improvements in ocean carbon modeling. The first is the role of the Southern Ocean in climate forcing. The research aims to quantify its rates of water mass transfer associated with different circulations, to understand why water mass transformations differ greatly between models, and to analyze the relative contributions to numerical simulation uncertainties from physical and biogeochemical model components. The second is the capacity of the ocean to sequester carbon. The research addresses the nutrient limitation of CO_2 fertilization in the tropical oceans, which are among the regions with the greatest sources of uncertainty in the carbon cycle over the next half century.

These activities will address Goals 1, 2, 3, 4, and 5 and Questions 7.1, 7.2, 7.3, and 7.4 of the CCSP Strategic Plan.



Global Carbon Analysis. The carbon cycle is an integrated global system, and a complete understanding of changes in atmospheric CO_2 and CH_4 concentrations requires a global analysis of carbon sources and sinks and their dynamics at relevant spatial and temporal scales.

- *Global Carbon Cycle Modeling and Analysis* – New research investments for FY 2009 will focus on developing new or improved carbon models that are more comprehensive in treating significant processes and drivers, including those involving or stemming from human activities. These advanced carbon models will address time scales of decades to centuries and integrate across spatial scales up to the global scale. One important focus for improving and extending the treatment of fundamental processes in carbon cycle models is to advance the coupling of global carbon and climate models allowing analyses of interactions and feedbacks within the coupled carbon and climate systems. New research will seek also to extend carbon data assimilation or data fusion schemes by incorporating models of major carbon cycle components with substantially improved detail, realism, and accuracy in the representation of key processes that determine magnitudes and distributions of sources and sinks for carbon and carbon cycle dynamics affecting CO_2 or CH_4 concentrations. New research will be conducted to prepare atmospheric transport and inversion models and data assimilation and data fusion schemes to utilize measurements of atmospheric column CO_2 from the Orbiting Carbon Observatory.

These activities will address Goals 1, 2, 3, 4, and 5 and Questions 7.1, 7.2, 7.3, 7.4, and 7.5 of the CCSP Strategic Plan.

Carbon Management and Decision Support. Initial projects are nearing completion and others are underway that will allow government agencies, industry associations, and private landowners to use carbon management information derived from scientific observations, ecosystem models, and on-line tools (products of carbon cycle science research) for resource management and policy decisions affecting both the near and long term. These projects are have particular importance for forest management and agricultural practices.

- *Agriculture Systems and Emissions of Greenhouse Gases* – A decision-support system for controlling greenhouse gas emissions from agricultural cropping systems will be completed and tested using greenhouse gas emission data from the nationwide Greenhouse Gas Reduction through Agricultural Carbon Enhancement network (GRACEnet). A database of greenhouse gas emissions from crop, pasture, and rangeland systems in the United States will be made publicly available. Remote-sensing technologies for mapping crop residue cover and crop management practices that affect soil conservation and soil carbon will be refined and tested.
- *Monitoring Soil Resources in Agricultural Lands* – Increasing pressure on soil resources in combination with the need to understand how these resources are responding to changing climate has led to the development of a national soil-monitoring network. The monitoring network is currently evaluating soil carbon stock trends in the upper Midwest using a combination of soil sampling, satellite remote-sensing data, and modeling. The results will inform policymakers about carbon sources and sinks in agricultural regions, as well as form a basis for projections of greenhouse gas mitigation potential through carbon management practices. The monitoring network is being established with the USDA Natural Resources Conservation Service National Resources Inventory, which has provided long-term monitoring of land-use and management activity since the early 1980s. The network will provide invaluable information for evaluating the influence of climate forcing and management activity on soil resources, and will ensure long-term sustainability of agricultural production for society.

These activities will address Goals 1, 2, 3, 4, and 5
and Questions 7.1, 7.4, 7.5, and 7.6 of the CCSP Strategic Plan.

International Partnerships. Partnerships between scientists and governments to work on the coordination, synthesis, and interpretation of carbon data sets from around the world are essential for full global-scale syntheses, integrations, and future analysis.

- *North American Partners* – Under the framework of the U.S. Climate Change Bilaterals made from 2001 to 2003 with multiple industrialized and developing countries, government officials from Canada, Mexico, and the U.S. Carbon Cycle Interagency Working Group (CCIWG) recently agreed on a *Statement of Common Interests and Intent to Work Together on Carbon Cycle Research in North America* and endorsed a joint cooperative research effort to assess the North American carbon budget. In 2007, the three countries established the Joint North American Carbon Program and

formed a Joint NACP Science Steering Group and Joint Government Coordination Team to lead and facilitate the common activities of the joint cooperative.

- *Northern Hemisphere Partners* – To extend North American partnership efforts of the CCIWG beyond North America to the Northern Hemisphere (Europe and Asia), U.S. scientists broadened interests and cooperation with carbon science activities abroad. In 2007, the interagency working group initiated discussions with European Union (EU) officials under the framework of the U.S. Bilaterals and then in principle supported the early activities of European scientists leading the EU CarboEurope and CarboOcean programs on a proposed EU initiative to coordinate (network) data management activities on global carbon observations. The European Union and EU scientists aim to link European carbon observation research to similar existing programs in other countries as a contribution to the intergovernmental *ad hoc* Group on Earth Observations (GEO).
- *Global Partners* – The CCIWG initiated liaison proceedings with international nongovernmental organizations of the Earth System Science Partnership (ESSP). In 2006, the interagency working group established formal terms of reference with the ESSP Global Carbon Project (GCP), the GCP International Project Office, and the GCP Scientific Steering Committee (SSC). In 2007, the GCP SSC embraced the U.S. Carbon Cycle Science Program Office as their Affiliate Project Office in North America. The international link with the ESSP GCP is expected to yield stronger national program interactions, regional and global syntheses, and relevant deliverables on the global carbon budgets.

These activities will address Goals 2, 3, and 4 and Questions 7.4 and 7.5 of the CCSP Strategic Plan.

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