The Carbon Cycle

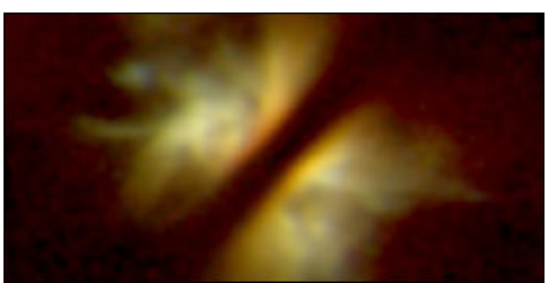
Carbon (C), the fourth most abundant element in the Universe, after hydrogen (H), helium (He), and oxygen (O), is *the* building block of life. It's the element that anchors all organic substances, from fossil fuels to DNA. On Earth, carbon cycles through the land, ocean, atmosphere, and the Earth's interior in a major biogeochemical cycle (the circulation of chemical components through the biosphere from or to the lithosphere, atmosphere, and hydrosphere). The global carbon cycle can be divided into two categories: the geological, which operates over large time scales (millions of years), and the biological/physical, which operates at shorter time scales (days to thousands of years).

"Carbon, the fourth most abundant element in the Universe, is the building block of life."

Carbon is the essential element for life on Earth. Not only is carbon found in all living things, the element is present in the atmosphere, in the layers of limestone sediment on the ocean floor, and in fossil fuels like coal. (Illustration by Robert Simmon, NASA GSFC)

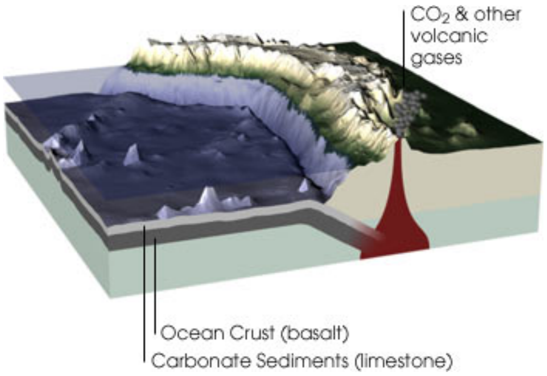
Geological Carbon Cycle

Billions of years ago, as planetesimals (small bodies that formed from the solar nebula) and carbon-containing meteorites bombarded our planet's surface, the carbon content of the solid Earth steadily increased.



All the carbon that cycles through the Earth's systems today was present at the birth of the solar system 4.5 billion years ago. The above image from the Hubble Space Telescope Near Infrared Camera and Multi-Object Spectrometer (NICMOS) shows a disk of gas and dust around a young star. [Image courtesy D. Padgett (IPAC/Caltech), W. Brandner (IPAC), K. Stapelfeldt (JPL) and NASA)]

Since those times, carbonic acid (a weak acid derived from the reaction between atmospheric carbon dioxide [CO_2] and water) has slowly but continuously combined with calcium and magnesium in the Earth's crust to form insoluble carbonates (carbon-containing chemical compounds) through a process called weathering. Then, through the process of erosion, the carbonates are washed into the ocean and eventually settle to the bottom. The cycle continues as these materials are drawn into Earth's mantle by subduction (a process in which one lithospheric plate descends beneath another, often as a result of folding or faulting) at the edges of continental plates. The carbon is then returned to the atmosphere as carbon dioxide during volcanic eruptions.



In the geological carbon cycle, carbon moves between rocks and minerals, seawater, and the atmosphere. Carbon dioxide in the atmosphere reacts with some minerals to form the mineral calcium carbonate (limestone). This mineral is then dissolved by rainwater and carried to the oceans. Once there, it can precipitate out of the ocean water, forming layers of sediment on the sea floor. As the Earth's plates move, through the processes of plate tectonics, these sediments are subducted underneath the continents. Under the great heat and pressure far below the Earth's surface, the limestone melts and reacts with other minerals, releasing carbon dioxide. The carbon dioxide is then re-emitted into the atmosphere through volcanic eruptions. (Illustration by Robert Simmon, NASA GSFC)

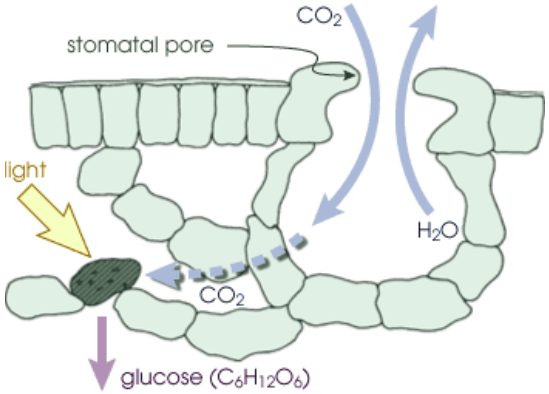
The balance between weathering, subduction, and volcanism controls atmospheric carbon dioxide concentrations over time periods of hundreds of millions of years. The oldest geologic sediments suggest that, before life evolved, the concentration of atmospheric carbon dioxide may have been one-hundred times that of the present, providing a substantial greenhouse effect during a time of low solar output. On the other hand, ice core samples taken in Antarctica and Greenland have led scientists to hypothesize that carbon dioxide concentrations during the last ice age (20,000 years ago) were only half of what they are today.

The Carbon Cycle

Biological/Physical Carbon Cycle: Photosynthesis and Respiration

Biology also plays an important role in the movement of carbon in and out of the land and ocean through the processes of photosynthesis and respiration. Nearly all forms of life on Earth depend on the production of sugars from solar energy and carbon dioxide (photosynthesis) and the metabolism (respiration) of those sugars to produce the chemical energy that facilitates growth and reproduction.

"Photosynthesis and respiration also play an important role in the long-term geological cycling of carbon."



During photosynthesis, plants absorb carbon dioxide and sunlight to create fuel—glucose and other sugars—for building plant structures. This process forms the foundation of the biological carbon cycle. (Illustration courtesy P.J. Sellers *et al.*)

Through the process of photosynthesis, green plants absorb solar energy and remove carbon dioxide from the atmosphere to produce carbohydrates (sugars). Plants and animals effectively “burn” these carbohydrates (and other products derived from them) through the process of respiration, the reverse of photosynthesis. Respiration releases the energy contained in sugars for use in metabolism and renders the carbohydrate“fuel” back to carbon dioxide. Together, respiration and decomposition (respiration that consumes organic matter mostly by bacteria and fungi) return the biologically fixed carbon back to the atmosphere. The amount of carbon taken up by photosynthesis and released back to the atmosphere by respiration each year is 1,000 times greater than the amount of carbon that moves through the geological cycle on an annual basis.

Photosynthesis and respiration also play an important role in the long-term geological cycling of carbon. The presence of land vegetation enhances the weathering of soil, leading to the long-term—but slow—uptake of carbon dioxide from the atmosphere. In the oceans, some of the carbon taken up by phytoplankton (microscopic marine plants that form the basis of the marine food chain) to make shells of calcium carbonate ($CaCO_3$) settles to the bottom (after they die) to form sediments. During times when photosynthesis exceeded respiration, organic matter slowly built up over millions of years to form coal and oil deposits. All of these biologically mediated processes represent a removal of carbon dioxide from the atmosphere and storage of carbon in geologic sediments.

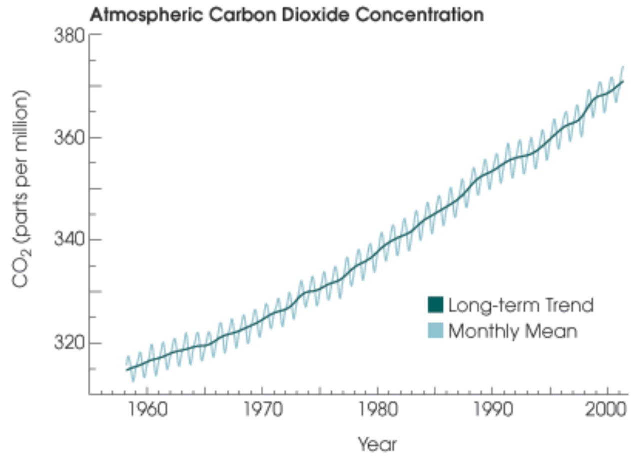
The Carbon Cycle

Carbon on the Land and in the Oceans: The modern carbon cycle

On land, the major exchange of carbon with the atmosphere results from photosynthesis and respiration. During the daytime in the growing season, leaves absorb sunlight and take up carbon dioxide from the atmosphere. In parallel, plants, animals and soil microbes consume the carbon in organic matter and return carbon dioxide to the atmosphere. When conditions are too cold or too dry, photosynthesis and respiration cease along with the movement of carbon between the atmosphere and the

"On land, the major exchange of carbon with the atmosphere results from photosynthesis and respiration."

land surface. The amounts of carbon that move from the atmosphere through photosynthesis, respiration, and back to the atmosphere are large and produce oscillations in atmospheric carbon dioxide concentrations (see Keeling curve). Over the course of a year, these biological fluxes of carbon are over ten times greater than the amount of carbon introduced to the atmosphere by fossil fuel burning.

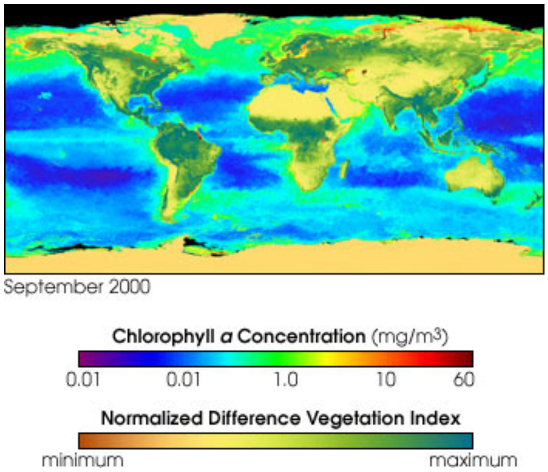


Carbon Dioxide in the atmosphere has been steadily rising since regular measurements began in 1958. The graph above shows both the long-term trend and the seasonal variation. (Graph by Robert Simmon, based on data from the NOAA Climate Monitoring & Diagnostics Laboratory)

Fire also plays an important role in the transfer of carbon dioxide from the land to the atmosphere. Fires consume biomass and organic matter to produce carbon dioxide (along with methane, carbon monoxide, smoke), and the vegetation that is killed but not consumed by the fire decomposes over time adding further carbon dioxide to the atmosphere.

Over periods of years to decades, significant amounts of carbon can be stored or released on land. For example, when forests are cleared for agriculture the carbon contained in the living material and soil is released, causing atmospheric carbon dioxide concentrations to increase. When agricultural land is abandoned and forests are allowed to re-grow, carbon is stored in the accumulating living biomass and soils causing atmospheric carbon dioxide concentrations to decrease.

In the oceans, carbon dioxide exchange is largely controlled by sea surface temperatures, circulating currents, and by the biological processes of photosynthesis and respiration. carbon dioxide can dissolve easily into the ocean and the amount of carbon dioxide that the ocean can hold depends on ocean temperature and the amount of carbon dioxide already present. Cold ocean temperatures favor the uptake of carbon dioxide from the atmosphere whereas warm temperatures can cause the ocean surface to release carbon dioxide. Cold, downward moving currents such as those that occur over the North Atlantic absorb carbon dioxide and transfer it to the deep ocean. Upward moving currents such as those in the tropics bring carbon dioxide up from depth and release it to the atmosphere.



The above image show the global biosphere. The Normalized Difference Vegetation Index measures the amount and health of plants on land, while chlorophyll *a* measurements indicate the amount of phytoplankton in the ocean. Land vegetation and phytoplankton both consume atmospheric carbon dioxide. (Image courtesy the SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE)

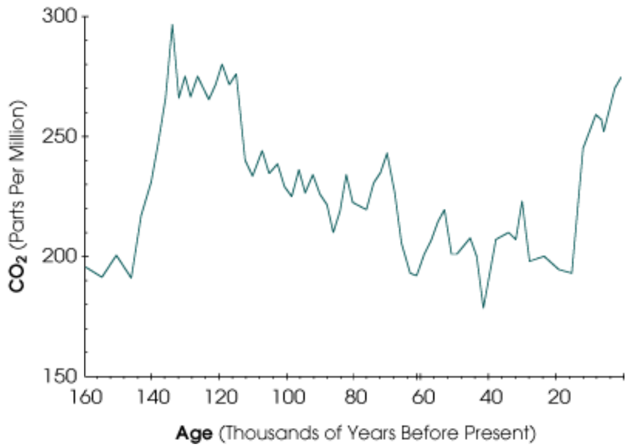
Life in the ocean consumes and releases huge quantities of carbon dioxide. But in contrast to land, carbon cycles between photosynthesis and respiration vary rapidly; i.e., there is virtually no storage of carbon as there is on land (i.e., tree trunks and soil). Photosynthetic microscopic phytoplankton are consumed by respiring zooplankton (microscopic marine animals) within a matter of days to weeks. Only small amounts of residual carbon from these plankton settle out to the ocean bottom and over long periods of time represent a significant removal of carbon from the atmosphere.

The Carbon Cycle

The Human Role

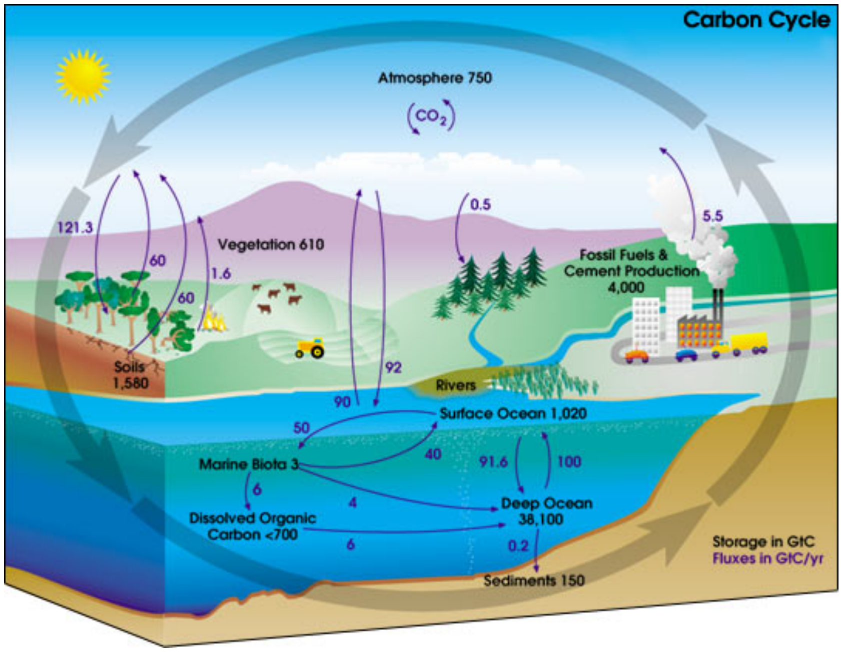
In addition to the natural fluxes of carbon through the Earth system, anthropogenic (human) activities, particularly fossil fuel burning and deforestation, are also releasing carbon dioxide into the atmosphere. When we mine coal and extract oil from the Earth's crust, and then burn these fossil fuels for transportation, heating, cooking, electricity, and manufacturing, we are effectively moving carbon more rapidly into the atmosphere than is being removed naturally through the sedimentation of carbon, ultimately causing atmospheric carbon dioxide concentrations to increase. Also, by clearing forests to support agriculture, we are transferring carbon from living biomass into the atmosphere (dry wood is about 50 percent carbon). The result is that humans are adding ever-increasing amounts of extra carbon dioxide into the atmosphere. Because of this, atmospheric carbon dioxide concentrations are higher today than they have been over the last half-million years or longer.

"Humans are adding ever-increasing amounts of extra CO_2 into the atmosphere."



The long-term record of atmospheric carbon dioxide obtained from Antarctic ice cores shows huge fluctuations over the past 150,000 years. Periods of low carbon dioxide concentration correspond to ice ages, while higher carbon dioxide concentrations are linked to warmer periods. The last ice age ended 10,000 to 20,000 years ago, as carbon dioxide levels rose from below 200 parts per million to about 280 parts per million. Current atmospheric carbon dioxide levels are above 370 parts per million because of the burning of fossil fuels. This has raised concern in the scientific community that average global temperatures may rise as a result. (Graph by Robert Simmon, based on data from Lorius, C., J. Jouzel, C. Ritz, L. Merlivat, N.I. Barkov, Y.S. Korotkevitch, and V.M. Kotlyakov. 1995. A 150,000-year climatic record from Antarctic ice. *Nature* 316:591-596.)

Not all of the carbon dioxide that has been emitted by human activities remains in the atmosphere. The oceans have absorbed some of it because as the carbon dioxide in the atmosphere increases it drives diffusion of carbon dioxide into the oceans. However, when we try to account for sources and sinks for carbon dioxide in the atmosphere we uncover some mysteries. For example, notice in Figure 1 (schematic of the carbon cycle) that fossil fuel burning releases roughly 5.5 gigatons of carbon (GtC [giga=1 billion]) per year into the atmosphere and that land-use changes such as deforestation contribute roughly 1.6 GtC per year. Measurements of atmospheric carbon dioxide levels (going on since 1957) suggest that of the approximate total amount of 7.1 GtC released per year by human activities, approximately 3.2 GtC remain in the atmosphere, resulting in an increase in atmospheric carbon dioxide. In addition, approximately 2 GtC diffuses into the world's oceans, thus leaving 1.9 GtC unaccounted for.



In any given year, tens of billions of tons of carbon move between the atmosphere, hydrosphere, and geosphere. Human activities add about 5.5 billion tons per year of carbon to the atmosphere. The illustration above shows total amounts of stored carbon in black, and annual carbon fluxes in purple. (Illustration courtesy NASA Earth Science Enterprise)

What happens to the leftover 1.9 GtC? Scientists don't know for sure, but evidence points to the land surface. However, at this time, scientists do not agree on which processes dominate, or in what regions of the Earth this missing carbon flux occurs. Several scenarios could cause the land to take up more carbon dioxide than is released each year. For example, re-growth of forests since the massive deforestation in the Northern Hemisphere over the last century could account for some of the missing carbon while changing climate could also contribute to greater uptake than release. The missing carbon problem illustrates the complexity of biogeochemical cycles, especially those in which living organisms play an important role. It is critically important that we understand the processes that control these sources and sinks so that we can predict their behavior in the future. Will these sinks continue to help soak up the carbon dioxide that we are producing? Or will they stop or even reverse and aggravate the atmospheric increases? With the use of satellites and field studies, NASA scientists will help to obtain crucial information on the carbon cycle.

The Carbon Cycle

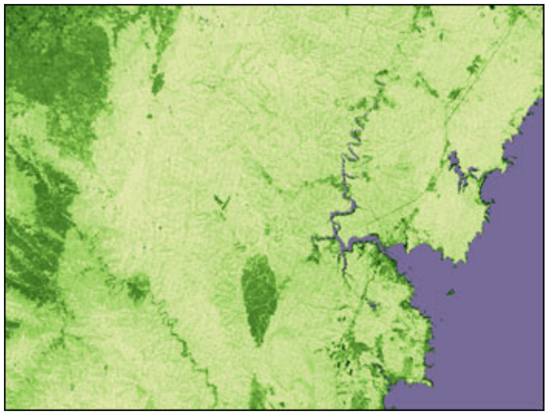
NASA Missions to Study the Global Carbon Cycle and Climate

Over the years, several NASA missions have studied various aspects of biology and climate. These studies have been augmented by data from operational weather satellites of the National Oceanic and Atmospheric Administration (NOAA).

The Landsat series of satellites, beginning in 1972, is the United States' oldest land-surface observation system. Landsat images have been used to study a wide range of processes, such as urban sprawl, deforestation, agricultural land-use trends, glaciation, and volcanic activity. The latest in the series, Landsat 7, launched in April 1999, is continuing to provide essential land-surface data to the scientific community. The Landsat 7 system is collecting and archiving an unprecedented quantity of high-quality

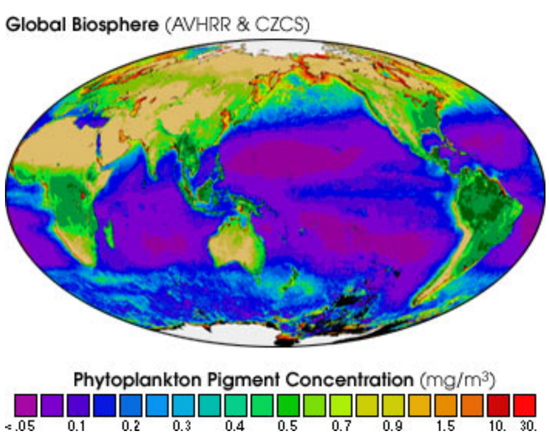
"Data sets from these NASA missions and campaigns are expected to lead to major advances in our understanding of the role of the global biosphere in climate change."

multispectral data each day. These new data are providing a high-resolution view of both seasonal and interannual changes in the terrestrial environment.



Instruments aboard the Landsat satellites measure vegetation at high resolution. The Multi-Spectral Scanner acquired this image of eastern Australia on December 9, 1982. Green indicates increasing density of vegetation. [Image courtesy Commonwealth Scientific & Industrial Research Organization (Australia)]

The launch of the Advanced Very High Resolution Radiometer (AVHRR) on TIROS-N in 1978, and on subsequent NOAA operational satellites, permitted the global mapping of sea surface temperature and vegetation. The launch of the Coastal Zone Color Scanner (CZCS) on Nimbus-7, also in 1978, made mapping oceanic chlorophyll and phytoplankton possible. The first step of photosynthesis both on land and in the oceans is the absorption of the sun's energy by the chlorophyll in leaves and phytoplankton. Scientist can measure the absorption of the sun's energy from space with satellites and consequently estimate the rates of carbon dioxide uptake by photosynthesis. Scientists at NASA's Goddard Space Flight Center produced the "First Picture of the Global Biosphere" using images from 15,000 orbits of the NOAA-7/AVHRR (for estimating land chlorophyll) and 66,000 images from the Nimbus-7/CZCS (for estimating oceanic phytoplankton chlorophyll referred to as "ocean color").

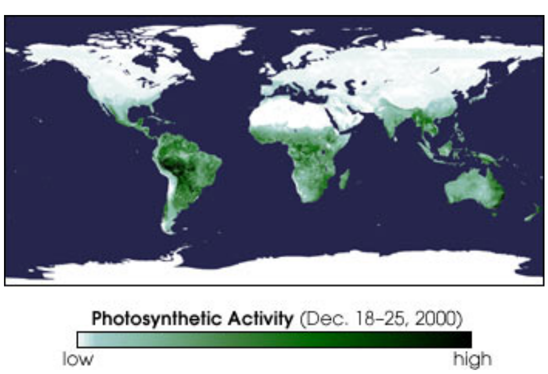


The first global image of the Earth's biosphere was created by NASA scientists using ocean data from the Coastal Zone Color Scanner (CZCS) and land data from the Advanced Very High Resolution Radiometer (AVHRR). Altogether, the data took almost 8 years to compile. Current satellite instruments like the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Moderate Resolution Imaging Spectroradiometer (MODIS) and can produce images like this roughly once a week. (Image courtesy NASA GSFC)

Launched in August 1997 as a successor to the CZCS, the SeaWiFS instrument onboard the OrbView-2 satellite acquires ocean color data to study the role of the oceans in the global carbon cycle, fluxes of trace gases at the air-sea interface, and ocean primary productivity (rate of carbon fixation from the atmosphere). As was learned from CZCS, subtle changes in ocean color signify various types and quantities of marine phytoplankton. Ocean color data from SeaWiFS are helping scientists identify ocean "hot spots" of biological activity, measure global phytoplankton biomass, and estimate the rate of oceanic carbon uptake. This information will yield a better understanding of the sources and sinks of the carbon cycle and the processes that shape global climate and environmental change.

Synthetic aperture radars on European, Japanese, and Canadian satellites, as well as NASA's Space Shuttle monitor deforestation and surface hydrological states and processes. The ability of synthetic aperture radars to penetrate cloud cover and dense plant canopies make them particularly valuable in rainforest and high-latitude boreal forest studies.

With the launch of the flagship EOS satellite in 1999—Terra—NASA is extending the measurements of ocean color and land vegetation with advanced spaceborne instruments. EOS instruments such as the Multi-Angle Imaging SpectroRadiometer (MISR) and the Moderate-Resolution Imaging SpectroRadiometer (MODIS) are providing global maps of surface vegetation so that scientists can model the exchange of trace gases, water, and energy between vegetation and the atmosphere. The Enhanced Thematic Mapper Plus (ETM+) onboard Landsat 7 and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) onboard EOS Terra are providing simultaneous multispectral, high-resolution observations of surface composition and natural hazards (volcanoes, floods, drought, etc.). In addition, MISR's ability to correct land-surface images for atmospheric scattering and absorption and sun-sensor geometry will allow better calculation of vegetation properties. The MOPITT (Measurements of Pollution in the Troposphere) instrument on Terra is providing global measurements of tropospheric methane and carbon monoxide.



New satellite sensors provide new ways of looking at Earth. In addition to measuring vegetation density, MODIS can also measure photosynthetic activity. This provides a more accurate estimate of the amount of carbon absorbed by plants. The image above shows photosynthetic activity during December 2000. Increasingly dark green indicates higher carbon consumption. (Image courtesy Peter Votava, University of Montana)

In addition to satellite and airborne missions, NASA, along with its international partners, conducts large-scale experiments in different types of vegetation (forests, grasslands, etc.) to build a better understanding of the carbon cycle.

The Boreal Ecosystem-Atmosphere Study (BOREAS) was a major international research program sponsored by NASA's Goddard Space Flight Center and carried out in the Canadian boreal forest. Its primary goals were to determine how the boreal forest interacts with the atmosphere (via the transfer of gases and energy), how much carbon is stored in the forest ecosystem, how climate change will affect the forest, and how changes in the forest affect weather and climate. Primarily conducted from 1994-1996 (with some experiments still continuing), BOREAS integrated ground, tower, airborne, and satellite measurements of the interactions between the forest ecosystem and the lower atmosphere. The findings from BOREAS are now being released.

The Large-Scale Biosphere-Atmosphere Experiment (LBA) is an international research initiative led by Brazil. It is designed to create new knowledge needed to understand the climatological, ecological, biogeochemical, and hydrological functioning of Amazonia, the impact of land-use change on these functions, and the interactions between Amazonia and the Earth system. The Amazon basin contains a large store of carbon, which may be exchanged with the atmosphere through (i) changes in land use brought about by fire, clearing, logging, planting and re-growth and (ii) changes in the balance between photosynthesis and respiration occurring as a result of variations in climate and atmospheric chemistry. Both types of change introduce uncertainties in the global carbon balance.

A major challenge for research within LBA is to determine both the human management-induced components and the climate-induced components of the net flux of carbon in the Amazon Basin. Of the 100 projects within LBA, 25 of them focus on understanding carbon exchange and storage throughout the Amazon. A new campaign will be launched in 2002 to complement *in situ* field and space-based system observations with airborne measurements of atmospheric gases and vegetation imaging.

Collectively, the resulting accurate, self-consistent, and long-term data sets from these NASA missions and campaigns are expected to lead to major advances in our understanding of the role of the global biosphere in climate change.

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