

## Overview

### DOE Workshop on Biological Carbon Cycling and Biosequestration Research

The focus of climate research nationally and globally has shifted to establishing the capability to more accurately project climate change and its impacts, and to better define mitigation and adaptation options. The science to achieve these new and much more challenging goals revolves around the development of Earth System Models (ESM) and the science to support them. These models combine physical climate models, global biological processes, and human activities. Understanding the global carbon cycle across terrestrial and ocean environments and its responses to climate change is essential for the viability of these models. The global carbon cycle is a balance between natural processes and emissions from human activities. This knowledge will provide the scientific underpinnings for more robust climate change modeling and help to identify carbon biosequestration-based mitigation strategies and human adaptation options over the coming decades. The Department of Energy's (DOE) energy security mission is dependent on this modeling and research capability.

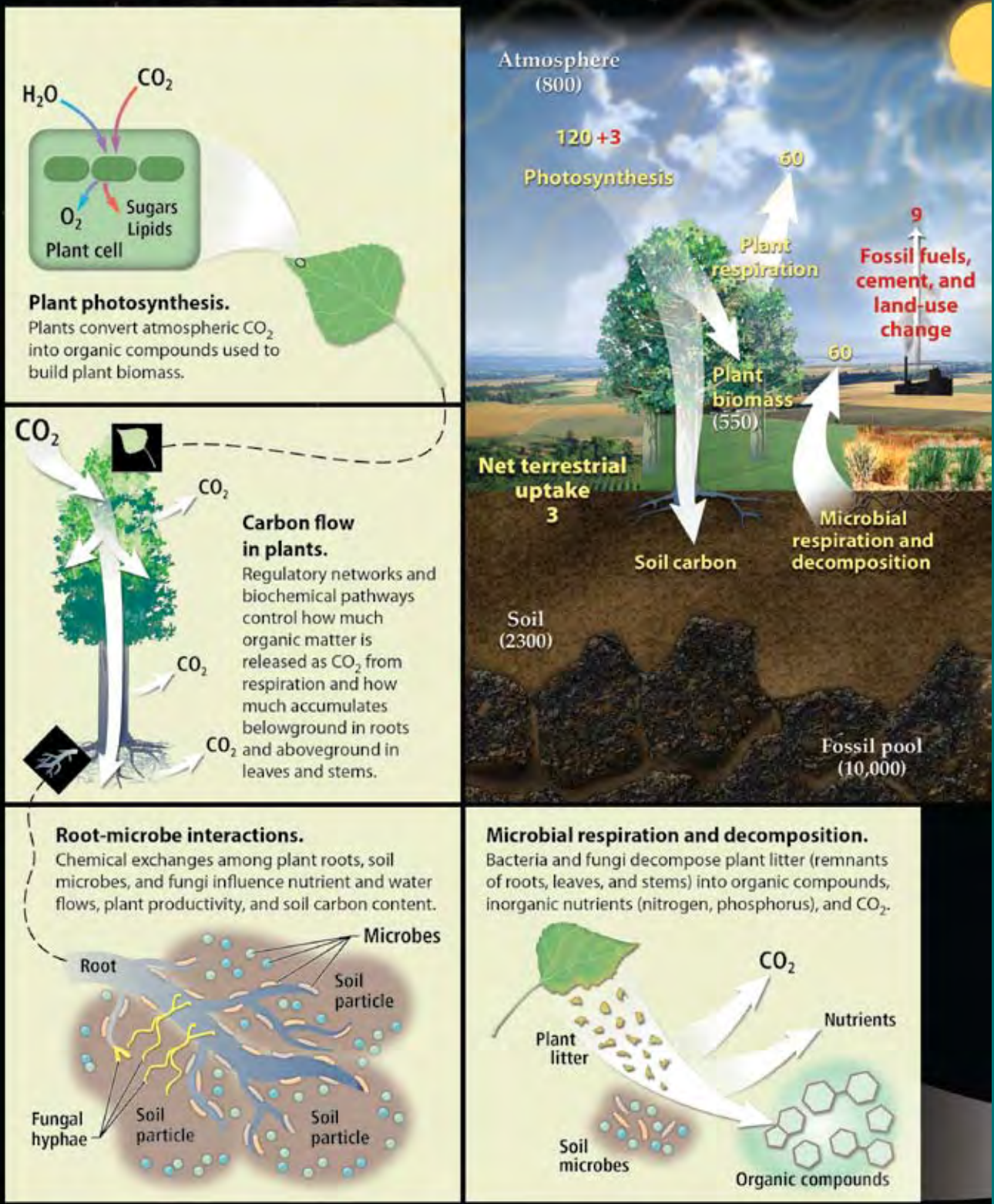
Increasing atmospheric CO<sub>2</sub> concentration is one of the most significant factors influencing future climate. There has been a rapid accumulation of heat-trapping CO<sub>2</sub> in the atmosphere [from 285 to 385 parts per million by volume (ppmv) since the Industrial Revolution], largely due to human activities—primarily fossil energy use. Strategies to minimize changes in climate will require that energy production and use be put in the context of Earth's natural biogeochemical cycling of carbon and other elements.

The DOE Office of Biological and Environmental Research (OBER) programs focus on increasing our understanding of carbon cycling in Earth's marine and terrestrial ecosystems, examining potential means of biological sequestration of carbon, and determining how climate change affects biological processes that influence carbon cycling and biosequestration (altered carbon cycling in managed ecosystems). Contributing to DOE's energy security mission, OBER supports research programs emphasizing the development of integrative, systems-level approaches to study the diverse natural capabilities and behaviors of plants, microorganisms, and the communities in which they reside. DOE OBER also facilitates development of breakthrough biotechnologies for urgent national priorities, including climate change research. Of particular interest is the interaction of genome-encoded processes in plant and microbial communities with environmental conditions. These studies will be critical in developing increasingly sophisticated models of global biogeochemical cycling and its response to climate change as well as informing potential carbon biosequestration strategies (see Fig. 1.1. Components of the Global Carbon Cycle, pp. 2–3).

To help develop program objectives in biological carbon cycling and biosequestration, OBER hosted the Carbon Cycling and Biosequestration Workshop in March 2008. Experts in terrestrial and ocean biogeochemical cycling, ecosystem science, research technology development, and modeling met to identify research needs and opportunities for understanding biological carbon cycling and biosequestration, assess current science and technology, and describe fundamental research that can

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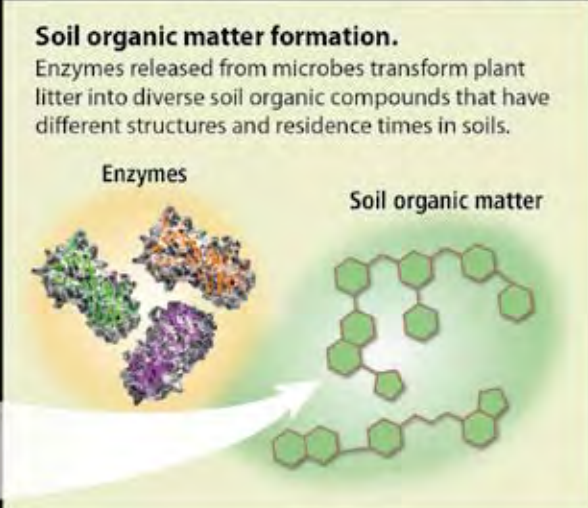
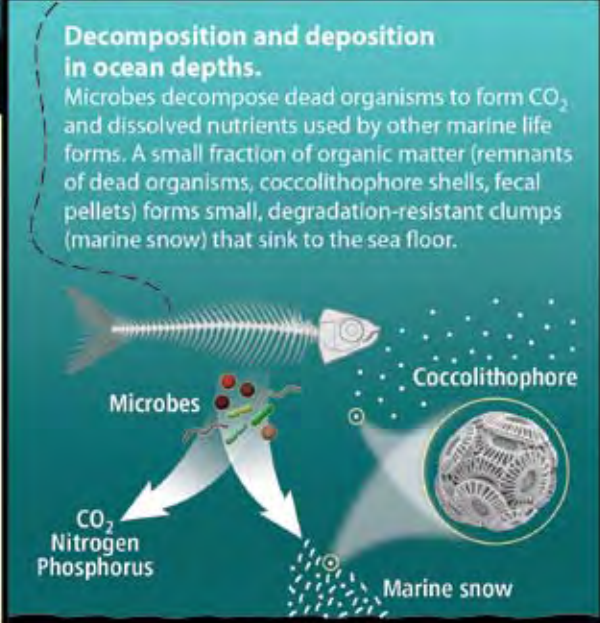
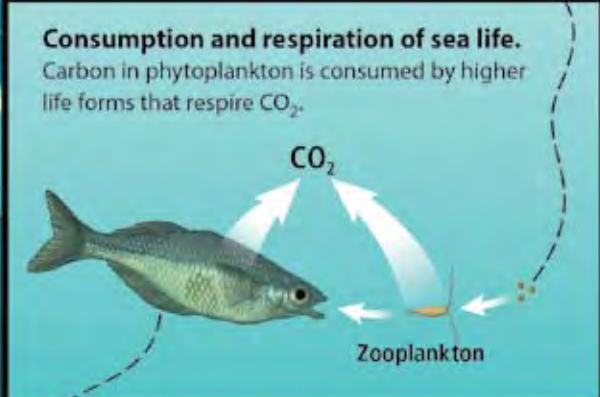
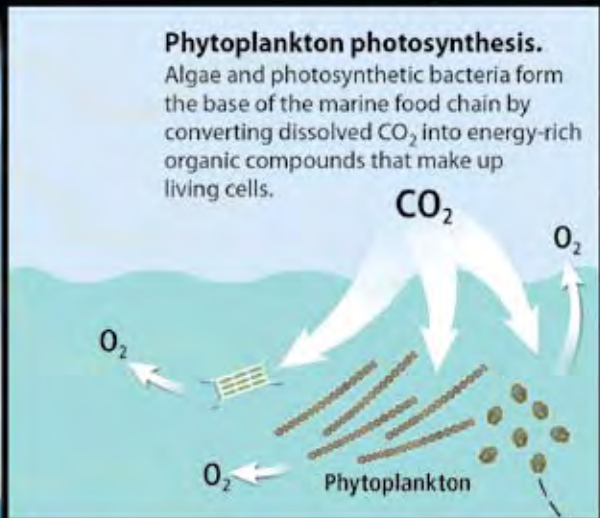
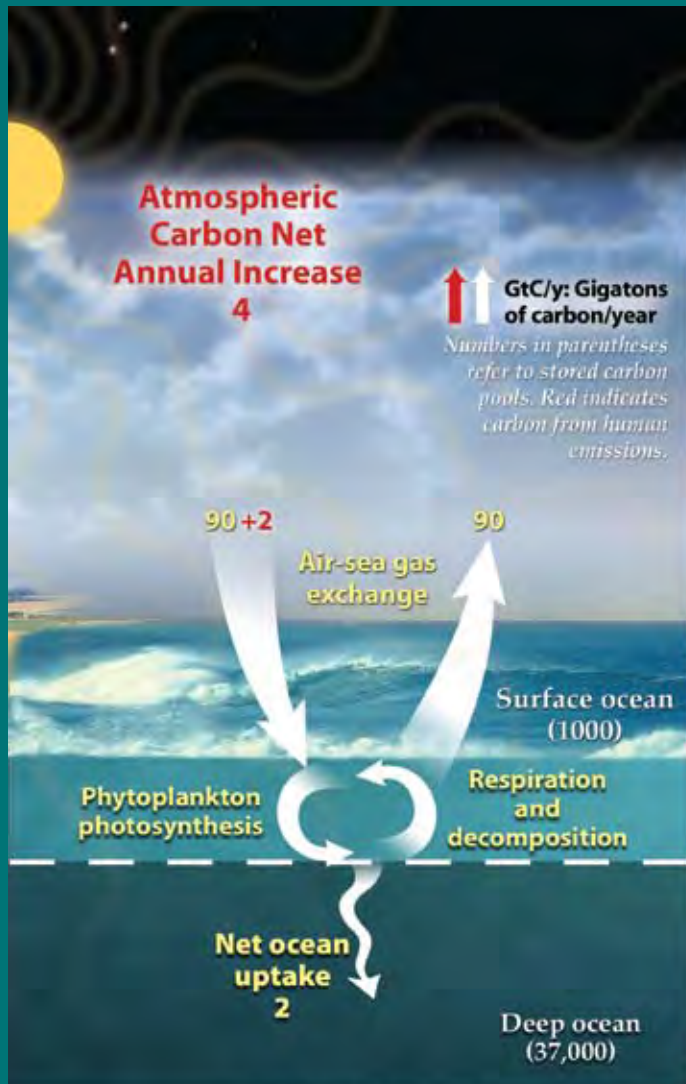
# Components of the Global Carbon Cycle



**Fig 1.1. Components of the Global Carbon Cycle.** A simplified representation of the contemporary global carbon cycle is shown in the center of this figure. Values in parentheses are estimates of the main carbon reservoirs in gigatons (GT) as reported in Houghton (2007). The natural flux between the terrestrial biosphere and the atmosphere is about 120 GT

of carbon per year, and that between the oceans and atmosphere is about 90 GT per year (IPCC 2007). In the terrestrial biosphere, photosynthesis removes about 120 GT of carbon from the atmosphere; decomposition of biological material and respiration from plants and soil microbes return 120 GT of carbon.

In the oceans, the marine biosphere does not take up  $\text{CO}_2$  directly from the atmosphere. Each year the oceans absorb and release about 90 GT of carbon largely via diffusion across the air-ocean interface. The physical processes controlling the sinking of  $\text{CO}_2$  into colder, deeper waters (where  $\text{CO}_2$  is more soluble) and the mixing of ocean water at intermediate



depths are known collectively as the “solubility pump.” Phytoplankton photosynthesis converts CO<sub>2</sub> into organic carbon that is largely returned to ocean water as CO<sub>2</sub> via microbial respiration and decomposition. The “biological pump” refers to the small fraction of organic carbon that forms into degradation-resistant clumps and sinks to the ocean floor.

Together the solubility and biological pumps control the amount of carbon transported to ocean depths and the exchange of CO<sub>2</sub> between ocean and atmosphere.

Human activities (primarily fossil fuel use) emit about 9 GT of carbon each year. About 4 GT of this human-contributed carbon remain in the atmosphere; 3 GT are taken up by natural

terrestrial processes, and another 2 GT are removed by the ocean (Canadell et al. 2007).

Peripheral boxes describe some of the biological processes (photosynthesis, partitioning, respiration, and organic-matter formation) discussed in this report that play key roles in regulating the flow of carbon in and out of terrestrial and ocean ecosystems.

be pursued to meet OBER goals. This report outlines the workshop's findings and highlights key opportunities for biological carbon cycling research.

## Introduction

Energy production worldwide is significantly altering the atmospheric concentration of CO<sub>2</sub>. When fossil fuels are consumed, carbon sequestered deep within the Earth for eons is added to the global carbon cycle. Fossil CO<sub>2</sub> emitted from smokestacks and tailpipes flows into one of three reservoirs with physical and biological components: the atmosphere, oceans, and terrestrial systems. The complex carbon flows and transformations among these major Earth system components make up the carbon cycle. These natural exchanges of carbon between the biosphere and Earth's physical components are many times greater than the 9 billion tons [gigatons (GT)] produced by humans each year (see Table 1.1. Annual Fluxes in Global Carbon, this page, and Fig. 1.1, pp. 2–3). The biological processes of photosynthesis and respiration largely control the annual flux of about 120 GT of carbon between the atmosphere and land. About 90 GT of carbon flow in and out of the ocean, primarily through air-sea exchange at the surface.

Natural carbon sinks on land and in the oceans absorb about half the 9 GT of anthropogenic carbon emitted annually (Canadell et al. 2007). Although CO<sub>2</sub> emissions from human activities may seem insignificant relative to large natural carbon fluxes and stocks, they can shift the critical balance of the carbon cycle over time. The effective lifetime of CO<sub>2</sub> in the atmosphere exceeds centuries, so even relatively small imbalances can accumulate to significant atmospheric concentrations over hundreds of years. As anthropogenic CO<sub>2</sub> emissions continue to

grow and atmospheric concentrations reach levels unprecedented in the last 650,000 years based on Antarctic ice-core data, the risks associated with perturbing natural carbon fluxes and the balance of Earth's climate system increase.

These considerations define the pressing national need for a comprehensive understanding of the global carbon cycle across terrestrial and ocean environments. This knowledge will provide the scientific bases for more robust climate change modeling and help define options for carbon biosequestration over the coming decades. Greater understanding and predictive capabilities underpin six elements of national and international climate research strategies (see sidebar, Current Climate Research Strategies and their Dependence on Understanding the Global Carbon Cycle, p. 5).

## Accurate Climate Projections, Effective Mitigation and Adaptation Strategies Depend on Understanding the Global Carbon Cycle

One of the major challenges for 21<sup>st</sup> Century climate research is decreasing the uncertainties associated with how oceans and terrestrial ecosystems will respond to a warmer, higher-CO<sub>2</sub> world. Results from first-generation coupled climate–carbon cycle models suggest that as the Earth continues to warm, the capacity of the ocean and terrestrial biosphere to absorb anthropogenic CO<sub>2</sub> could peak by

**Table 1.1. Annual Fluxes in Global Carbon**  
(Gigatons of carbon per year)

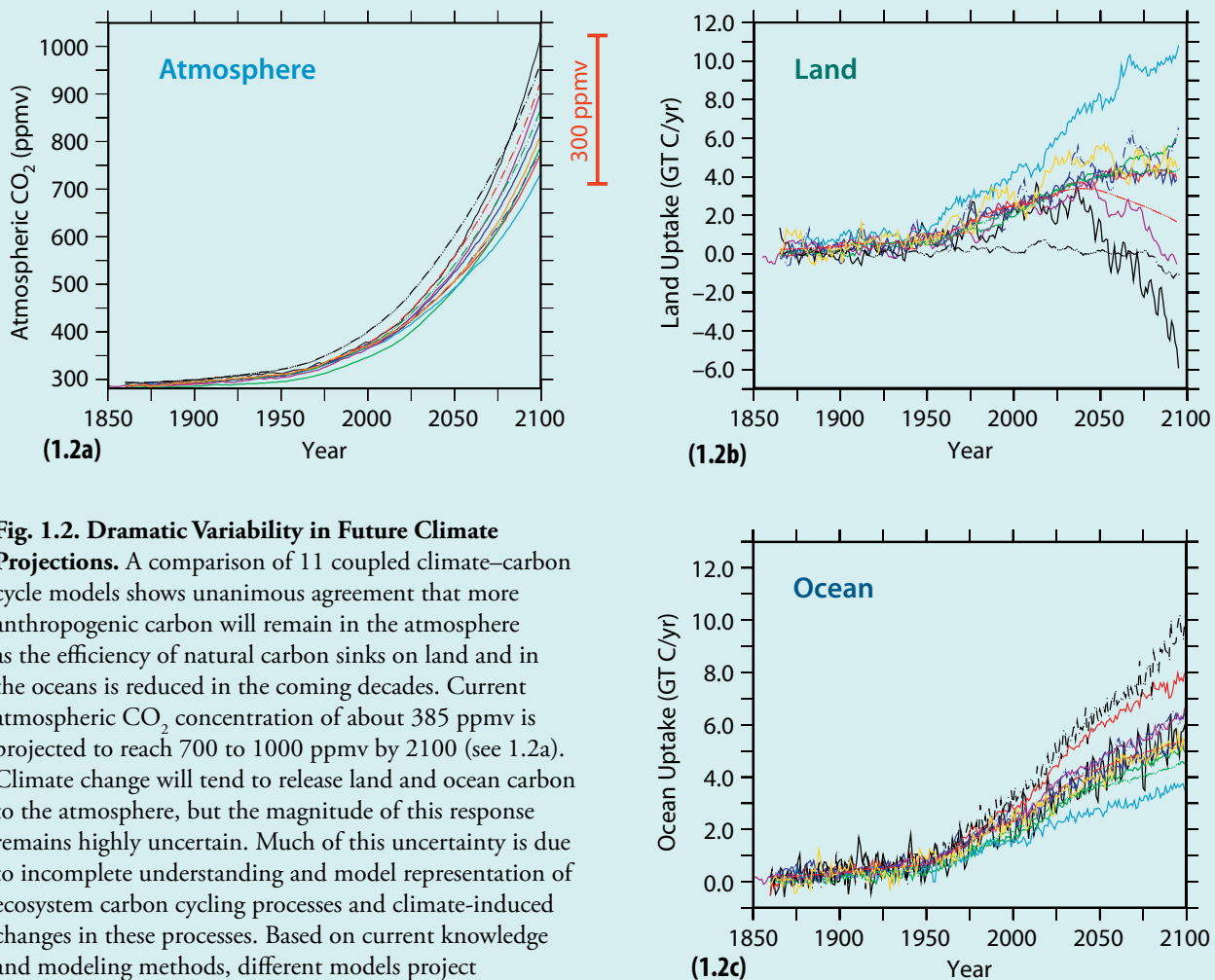
<b>Gross Natural Land-Atmosphere Carbon Fluxes<sup>1</sup></b>	
From atmosphere to plants	120
To atmosphere from plants	60
To atmosphere from soils	60
<b>Gross Natural Ocean-Atmosphere Carbon Fluxes<sup>1</sup></b>	
From atmosphere to oceans	90
To atmosphere from oceans	90
<b>Anthropogenic Carbon Emissions<sup>2</sup></b>	
To atmosphere from fossil fuel use	7.6
To atmosphere from land-use change	1.5
<b>Total</b>	<b>9.1*</b>
<b>Fate of Anthropogenic Carbon Emissions<sup>2</sup></b>	
Added to atmosphere	4.1*
Absorbed by natural processes on land	2.8*
Absorbed by natural processes in oceans	2.2*
<sup>1</sup> Source: IPCC 2007.	
<sup>2</sup> Source: Canadell et al. 2007.	
*Rounded to whole numbers in Fig. 1.1, pp. 2–3.	

## Current Climate Research Strategies and their Dependence on Understanding the Global Carbon Cycle

Yearly net atmospheric greenhouse gas emissions include carbon dioxide produced by human activity and that released naturally by terrestrial and ocean systems in the global carbon cycle. Contributing to this cycling of carbon among the atmosphere, land, and sea are carbon sources and sinks from physicochemical processes (e.g., the ocean's absorption and mineralization of carbon) and biological processes in terrestrial and ocean systems. Improved understanding of these components and their role in atmospheric retention of CO<sub>2</sub>, especially that produced by energy use, is essential to DOE development of carbon mitigation and biosequestration strategies. Accurate climate projections and potential carbon biosequestration options critically depend on descriptive, predictive models of ocean and terrestrial ecosystems and their contributions to the global carbon cycle.

Current needs for climate projection and carbon biosequestration research strategies include:

- 1. Incorporation of Increased Climate Knowledge into Models.** Better understanding and model representations of the historical climate record in the context of human activities, natural variability, and global processes that include the carbon cycle form the foundation for making meaningful climate projections and assessing human impacts on the global flow of carbon.
- 2. Near-Term Projections of Climate Change and Impacts.** High-resolution spatial analyses of climate change over the next few decades will focus on understanding the effects of such change (e.g., potential shifts in precipitation and weather, including extremes) at the regional scale to support development of mitigation and adaptation strategies.
- 3. Long-Term Projections of Climate Change and Ecosystem Feedbacks.** Earth System Models and others (e.g., dynamic vegetation simulations showing species succession in ecosystems) that incorporate advanced understanding of the global carbon cycle and other aspects of the biosphere affected by climate change will project potential climate shifts over centuries and longer. Projections for such time scales are critical for assessing the effects of increasing climate change, expanding human activities, and ensuing ecosystems-climate feedbacks. Such modeling endeavors require understanding not only the current and evolving physiology and functionality of ecosystems, but their transformations on various projected climate trajectories.
- 4. Emission Budgets.** A better understanding of the global carbon cycle, under changing climate conditions, is necessary to accurately predict effects of future human activities and provide viable energy infrastructure options. All projection scenarios of atmospheric CO<sub>2</sub> concentrations require data on human emission budgets (e.g., energy generation and use, industrial activities, and land-use change) to support national and global energy options and strategies. Current climate modeling calls for emission and atmospheric-concentration trajectories that explicitly require quantifying carbon sinks and sources to derive atmospheric CO<sub>2</sub> concentrations.
- 5. Definition of Viable Carbon Biosequestration Strategies.** Carbon biosequestration strategies require understanding the behaviors of sources and sinks under changing climate and environmental conditions to potentially manage them for optimum carbon capture and long-term storage and mitigation of anthropogenic CO<sub>2</sub>.
- 6. Projecting Impacts on Goods and Services Derived from Ecosystems.** Closely connected to understanding and quantifying carbon flow within ecosystems are the goods and services such systems provide to society. Understanding climate impacts on goods and services is necessary for assessing adaptation options. These impacts are measured in the variations in goods and services as climate varies. Goods include food, feed, fiber, fuel, pharmaceutical products, and wildlife. Services include maintenance of hydrologic cycles, cleansing (filtering) of water and air, regulation of climate and weather, storage and cycling of nutrients, provision of habitat, and aesthetics. Ecosystems' carbon-carrying capacity and stocks are becoming critical components of their services.



**Fig. 1.2. Dramatic Variability in Future Climate**

**Projections.** A comparison of 11 coupled climate–carbon cycle models shows unanimous agreement that more anthropogenic carbon will remain in the atmosphere as the efficiency of natural carbon sinks on land and in the oceans is reduced in the coming decades. Current atmospheric CO<sub>2</sub> concentration of about 385 ppmv is projected to reach 700 to 1000 ppmv by 2100 (see 1.2a). Climate change will tend to release land and ocean carbon to the atmosphere, but the magnitude of this response remains highly uncertain. Much of this uncertainty is due to incomplete understanding and model representation of ecosystem carbon cycling processes and climate-induced changes in these processes. Based on current knowledge and modeling methods, different models project dramatically different futures for carbon uptake by land

(see 1.2b) and ocean (see 1.2c). More observational and experimental data are needed to constrain these models and decrease the large uncertainties in future projections of climate-induced changes in the carbon cycle. [Source: Figure adapted from Friedlingstein, P., et al. 2006. “Climate–Carbon Cycle Feedback Analysis: Results from the C<sup>4</sup>MIP Model Intercomparison,” *Journal of Climate* **19**, 3337–53. Reproduced by permission of the American Meteorological Society (AMS).]

mid-century and then stabilize or decrease (IPCC 2007). Terrestrial carbon sinks are projected to saturate, thus a better understanding of the temperature sensitivity of long-term soil carbon pools is needed. In oceans, rising temperatures and CO<sub>2</sub> levels are projected to decrease CO<sub>2</sub> solubility, increase acidification in surface waters, and reduce the vertical mixing of nutrients from the deep ocean, which would limit marine photosynthesis. Key uncertainties in the biological processes influencing these general projections remain.

In a recent comparison, when different climate–carbon models were supplied with nearly identical human emissions scenarios, these selected models—because they contained a variety of representations of global carbon cycle processes and treatments of interactions with climate—produced dramatically different projections for carbon uptake by land and ocean systems (Friedlingstein et al. 2006). For example, projections of CO<sub>2</sub> uptake by terrestrial ecosystems vary so widely that some models predict land to become a stronger sink, capturing up to 10 GT of carbon per year, whereas other models project land to become a carbon source, emitting up to 6 GT per year (see Fig. 1.2. Dramatic Variability in Future Climate Projections, this page). Two key

factors contributing to this wide variation in model output are (1) a limited understanding of potential biological responses and other feedbacks and (2) uncertainties in how to model these phenomena.

To improve the fidelity and accuracy of climate projections, the scientific community needs a better understanding of the fundamental mechanisms controlling carbon sources and sinks. In the past two decades, much progress has been made in understanding historical trends in atmospheric CO<sub>2</sub>, and biogeochemical modeling of carbon in oceans and terrestrial systems continues to advance. However, current carbon cycle research still cannot *quantitatively* address several key questions, including the following.

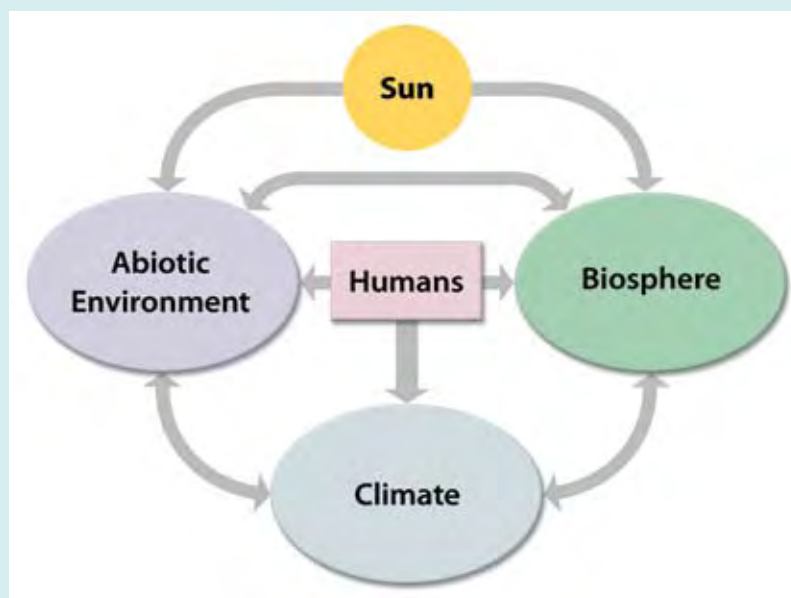
- What are the fundamental processes controlling the behaviors of carbon sinks and sources in ocean and terrestrial systems?
- How will human activities and changing climate conditions affect these processes?
- Will current carbon sinks persist or become carbon sources in a warmer, higher-CO<sub>2</sub> world?
- How long will biologically sequestered carbon remain stored?

Climate is both a product and a catalyst of interactions between a region's physical environment and the biosphere, all of which are driven by the sun and affected by human activities (see Fig. 1.3. Biosphere-Environment-Human-Climate Interactions, this page). The challenge is relating all these factors. Quantifying photosynthesis, respiration, and other biological processes that are components of carbon cycling is difficult because the metabolic flux of material and energy through cells, organisms, and ecosystems is tightly linked to a particular region's abiotic environmental factors (e.g., temperature, precipitation amounts and timing, geographical features, nutrient availability, length of days and seasons, and sunlight exposure). The range of geographic and ecophysiological regions to consider in models is enormous, but to truly understand how climate will affect valued goods and services (e.g., food, fiber, fuel, water and air quality, wildlife habitats, recreation, and aesthetics), climate projections must have the required detail to guide management decisions at both global and regional scales.

## Biology's Critical Role in the Carbon Cycle

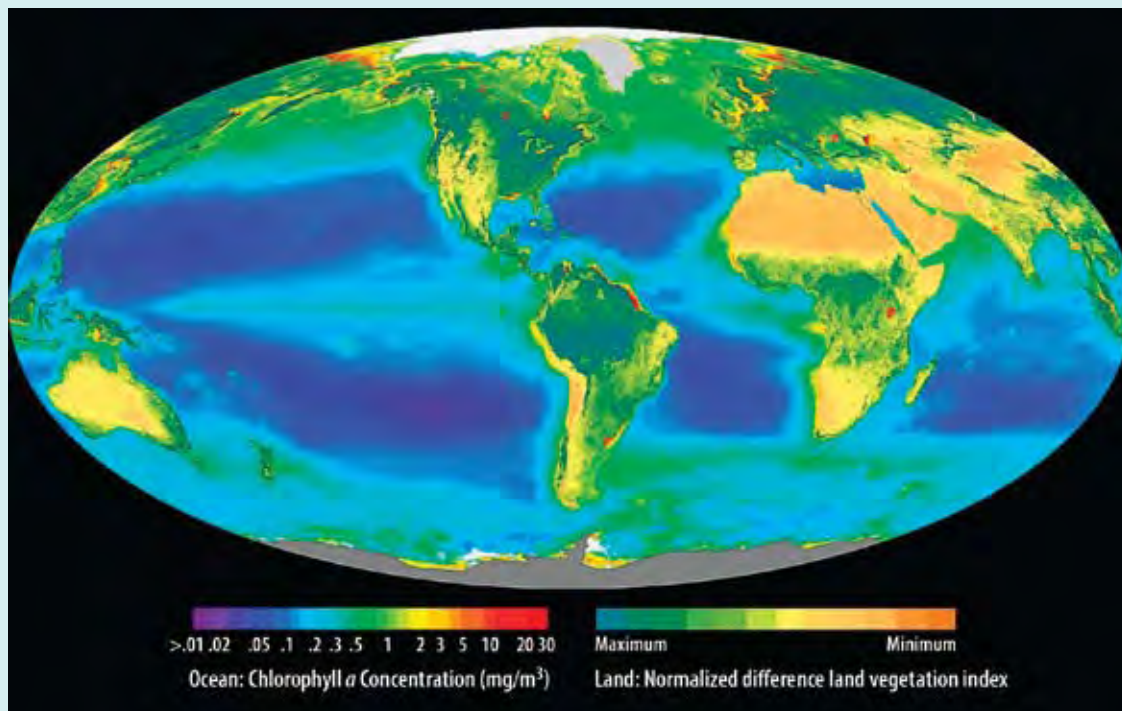
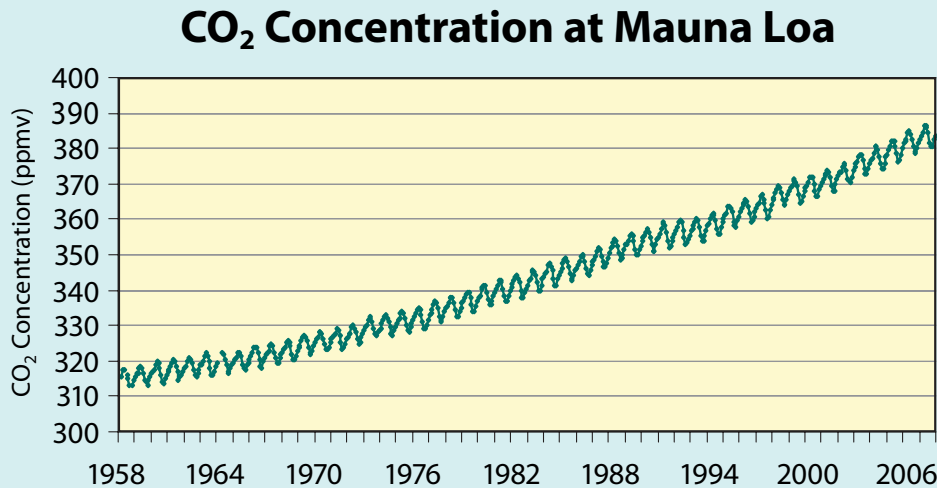
Biological processes drive the carbon cycle and other elemental cycles in globally significant ways. Eons ago, microbial metabolism created the oxygen-rich atmosphere that sustains much of life today, and the net effects of biological processes are observed in measurements of atmospheric CO<sub>2</sub> levels (see Fig. 1.4. Biological Influence on Atmospheric Carbon Dioxide Concentration, p. 8).

The global carbon cycle is dominated by two tightly interlinked processes: photosynthesis and respiration. Photosynthesis by plants and marine microbes



**Fig. 1.3. Biosphere-Environment-Human-Climate Interactions.**

**Fig. 1.4. Biological Influence on Atmospheric Carbon Dioxide Concentration.** The zigzag pattern in Mauna Loa atmospheric CO<sub>2</sub> measurements results from seasonal carbon flows between the atmosphere and biosphere. Greater landmass and deciduous vegetation in the Northern Hemisphere cause a drop in atmospheric CO<sub>2</sub> as photosynthesis fixes large amounts of CO<sub>2</sub> in spring and summer. In fall and winter, respiration and the decay of fallen leaves, combined with lower photosynthetic productivity, cause a net flow of CO<sub>2</sub> from the biosphere to the atmosphere. The upward slope of the trendline reflects the atmospheric increase of fossil CO<sub>2</sub> from human activities. [Source: Figure adapted from Keeling, R. F., S. C. Piper, A. F. Bollenbacher, and J. S. Walker. 2008. Atmospheric CO<sub>2</sub> records from sites in the SIO air sampling network. In *Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., USA. <http://cdiac.ornl.gov/trends/co2/graphics/mlo144e.pdf>.]



**Fig. 1.5. Photosynthesis in the Global Biosphere.** This NASA SeaWiFS image of the global biosphere shows the density of photosynthetic organisms on land and in the oceans. On land, the dark greens represent areas of abundant vegetation, with tans showing relatively sparse plant cover. In the oceans, red, yellow, and green regions depict dense blooms of phytoplankton (photosynthetic microbes), while blues and purples show regions of lower productivity. [Source: NASA SeaWiFS Project. <http://oceancolor.gsfc.nasa.gov/SeaWiFS/>.]



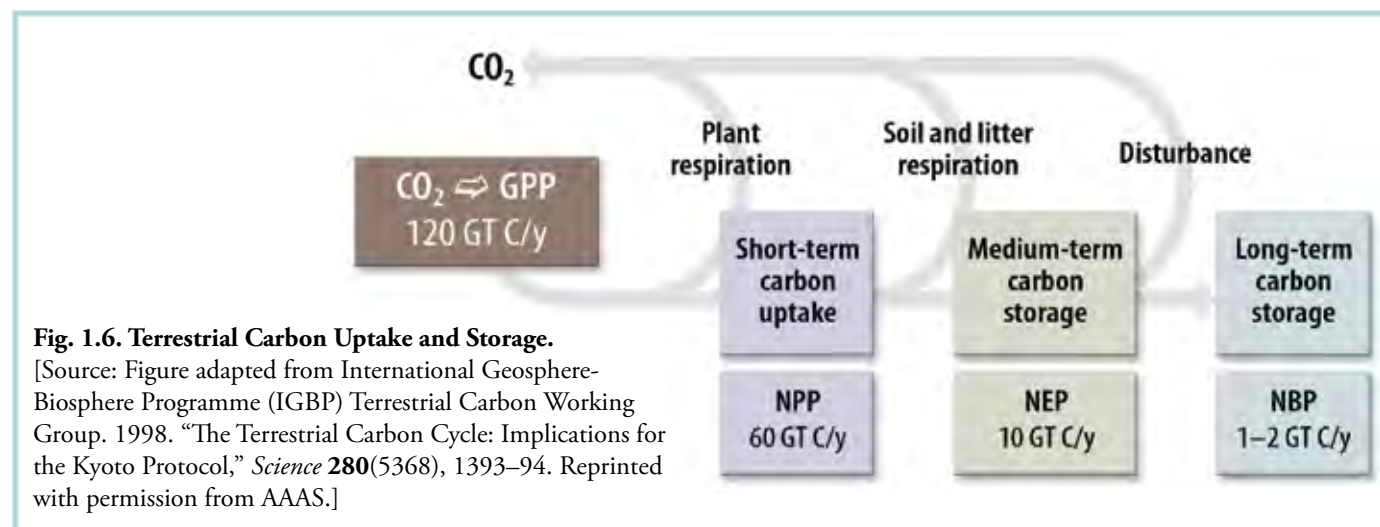
(see Fig. 1.5. Photosynthesis in the Global Biosphere, p. 8) removes  $\text{CO}_2$  from the atmosphere and converts or “fixes” it into organic material. This step of the cycle is referred to as primary production. Photosynthesis by phytoplankton and cyanobacteria in oceans converts about as much atmospheric carbon to organic carbon as does plant photosynthesis on land (Fuhrman 2003). The rate at which all photosynthetic organisms for a particular region or across the globe convert  $\text{CO}_2$  into organic compounds is known as gross primary productivity (GPP). Global GPP represents the largest flux of  $\text{CO}_2$  out of the atmosphere.

Organic carbon produced by photosynthesis is then either incorporated into biomass or respired for energy generation and released as  $\text{CO}_2$  and water. The rate of primary production that remains after accounting for losses through cellular respiration is called net primary productivity (NPP). Slight changes in the balance between photosynthesis and respiration can substantially impact atmospheric  $\text{CO}_2$  concentration (see Fig. 1.6. Terrestrial Carbon Uptake and Storage, this page).

Greater insight into the biological processes controlling the balance of photosynthesis and respiration is needed because the net result of these processes influences the fate of carbon in ecosystems. Understanding partitioning and the fate of carbon fixed by photosynthesis is equally important to investigating the impacts of rising  $\text{CO}_2$  levels on photosynthetic carbon assimilation. More research will be required to determine how plants regulate the allocation of fixed organic carbon used to increase biomass in photosynthetic plants or microbes versus the amount lost through cellular respiration and other processes.

Photosynthetic organisms are the original source of nearly all organic carbon in the biosphere. In terrestrial ecosystems, plants deposit detritus (plant and root litter) and root exudates into soils. In oceans, phytoplankton secrete cellular material into the water column, are lysed by viruses, and are grazed upon by zooplankton. A significant portion of the organic carbon liberated to the environment is rapidly respired by heterotrophic organisms and returned to the atmosphere as  $\text{CO}_2$ . More research is needed to determine how higher temperature, elevated  $\text{CO}_2$ , and other shifting environmental variables could alter the composition and metabolic activities of microbial communities that degrade organic carbon in soils and surface ocean waters.

The efficiency of carbon storage in biologically driven reservoirs is closely linked to the cycling and availability of nutrients. For terrestrial ecosystems, very little is known



## Types of Ecosystem Disturbances

**Disturbance:** Any abrupt event that drastically changes ecosystem characteristics such as population diversity, behavior, or climate response. A large-scale disturbance that rapidly converts vast quantities of stable organic carbon (e.g., forests) into CO<sub>2</sub> can impact the carbon cycle significantly. An ecosystem's state must be put in the context of its disturbance history to be meaningful.

### Climate-driven disturbance types

- Wildland fires
- Extreme events or severe weather (e.g., hurricanes and floods)
- Insects and disease
- Drought

### Anthropogenic disturbance types

- Conversion of forest or grassland to agriculture by human-mediated fires (such activity is an important overlap with climate-driven fire disturbances) or other methods
- Burning of agricultural waste products
- Implementation of biofuels and carbon biosequestration strategies
- Wood harvesting (products, fuels)
- Urbanization

about the fundamental mechanisms by which limitations in nutrients—especially those other than nitrogen and phosphorus—affect processes related to photosynthetic productivity and, ultimately, carbon biosequestration. In oceans, the abundance and ratio of nutrients rising from the deep determine community composition and activity of surface phytoplankton. Understanding how nutrient availability and other factors limit distribution of marine microbial communities and their diverse suite of nutrient transformations remains a major challenge (Arrigo 2005). In addition to the nutrient transfers among primary producers, grazers, predators, and decomposers, the symbiotic relationships between microbes and higher organisms to obtain limiting nutrients also are important to understanding integrated nutrient cycling; yet most symbiotic associations remain poorly characterized.

Nutrient cycles traditionally have been studied in isolation, but a more comprehensive understanding is needed of how these interconnected cycles function together. The molecular machines that mediate the biochemical reactions within the global metabolic network represent a set of genes essential to life and the biogeochemical cycling of carbon and other elements (Falkowski, Fenchel, and Delong 2008). A critical point is that the interconnections among these cycles exist in the interactions between species in a complex series of trophic cascades.

From the great diversity of biological processes that shape and sustain the Earth, can we define a core set of genes or functions essential to the biogeochemical cycling of carbon? Some key biological processes warranting more detailed scientific understanding were identified at the DOE carbon cycle workshop and are summarized in the sidebar, Key Biological Carbon Cycling Research Areas, p. 11, and in Fig. 1.1. Components of the Global Carbon Cycle, pp. 2–3.

## Ecosystem Response in a Changing Climate

Ecosystems undoubtedly will differ in their responses and vulnerability to climate change (IPCC 2007). While multiple factors may contribute to these differences, knowing the collective set of traits and functions present among different species within a community will be critical for determining rates and trajectories of ecosystem response, particularly net primary production and biosequestration of carbon. The ability of ecosystems to adapt to changing conditions will depend not only on a community's range of genome-encoded functions, but also on the sensitivity of organisms to alterations in nutrients and other limiting resources that regulate their fitness and abundance. The type and magnitude of resource alterations are the result of community response to environmental and anthropogenic shifts such as atmospheric nitrogen deposition, land-use change, habitat fragmentation, and variations in disturbance regimes.

Projections of mean carbon and nutrient stocks in vegetation, litter, and soil organic matter can vary greatly depending on the severity, frequency, and types of climate-related disturbances. Alterations in historical disturbance patterns resulting from a changing climate could have an overwhelming influence on the carbon cycle. More research is needed to quantify observed patterns in disturbance type, identify mechanisms driving the observed patterns, and develop a prognostic capability that can provide reasonable predictions for future disturbance patterns. Box 1.1, at left, Types of Ecosystem Disturbances, lists some of the most significant disturbances related to climate change and human activities.

## Key Biological Carbon Cycling Research Areas

### Terrestrial Ecosystem Processes

**Plant Photosynthesis.** Through photosynthesis, plants convert atmospheric CO<sub>2</sub> into organic compounds used to build plant biomass and drive metabolic and other processes. Research must reveal the impacts on enzymes and biochemical reactions underlying water loss and CO<sub>2</sub> exchange, nutrient uptake, and many other processes that control photosynthetic productivity as plants are subjected to changing levels of atmospheric CO<sub>2</sub> and climatic conditions.

**Mechanistic Understanding of Respiration.** Although the biochemistry of respiration and growth has been studied extensively, current understanding of respiration is limited by the lack of a mechanistic model. For certain levels of temperature increase, plants grown in high-CO<sub>2</sub> concentrations display increased biomass production and higher respiration rates, but the molecular and cellular mechanisms controlling this observed response need more detailed analysis. How plants acclimate to increasing temperature is another key area for investigation. In addition, distinguishing root respiration from microbial respiration in soils has proven especially difficult, yet doing so is important because each type of respiration responds differently to environmental signals, including those associated with climate change. New technologies for measuring carbon flux through metabolic pathways are becoming available and can help quantify respiratory carbon loss at cellular, microbial community, plant, and ecosystem levels.

**Partitioning of Carbon in Plant Biomass.** Carbon fixed by photosynthesis is translocated and partitioned among different plant compartments (e.g., leaves, stems, roots, and mycorrhizae), respired as CO<sub>2</sub>, or released as exudates into soil. The pattern of partitioning has feedback effects on photosynthetic capacity via leaf area and nutrient-uptake capacity through root deployment. Residence times of carbon compounds in these compartments vary greatly. Simple carbohydrates are metabolized in minutes to hours. Plant structural compounds can persist for years to decades. Although most plant compounds released into soils are consumed and respired by fungi and bacteria, a small fraction may be stored in long-lived pools for thousands of years. The regulatory systems and molecular controls for partitioning carbon among plant structures, cellular respiration, or release into different soil pools must be better understood and represented in models.

**Plant-Microbe Interactions in the Rhizosphere.** In the narrow zone of soil surrounding the root (the rhizosphere), fungal, bacterial, and archaeal interactions with plant roots can impact plant growth and development significantly. In turn, rhizosphere microbes obtain carbon and energy for growth from root exudates. Fungi and bacteria can enhance plant productivity by providing nutrients such as phosphorus and nitrogen or by suppressing plant pathogens in the soil. Glue-like proteins and other molecules secreted by rhizosphere fungi and bacteria form stabilized soil structures that support plant growth by increasing soil moisture and organic carbon content. Explicit chemical communications between plants and rhizosphere microbes facilitate these interactions.

**Characterization of the Plant Microbiome.** Plant surfaces and internal passages are colonized by a diverse array of microorganisms (collectively called the “microbiome”), many of which confer beneficial properties to their hosts. Interactions between plants and their resident microbial communities can influence plant metabolism, improve resistance to stress,

increase access to limiting nutrients, and deter pathogens. Understanding the nature and functions of the plant-associated microbiome and its potential importance to plant primary production is a key challenge.

**Microbial Processing of Plant Materials.** Soils represent the largest and most stable reservoir of carbon in terrestrial ecosystems and contain more than twice as much carbon as the atmosphere (Schlesinger 1997). Soil microbial communities mediate the multistep conversion of dead plant tissue and organic compounds exuded from plant roots into CO<sub>2</sub> or soil organic matter (SOM). The heterogeneous array of organic molecules composing SOM can reside in terrestrial ecosystems for decades to thousands of years. Microbial activity also contributes to the formation of mineral-organic matter complexes called microaggregates that physically protect organic carbon from degradation. Understanding the enzyme-catalyzed reactions and environmental conditions controlling the transformation of various SOM compounds into long-lived humic compounds or highly stable microaggregates could lead to opportunities for sequestering vast quantities of carbon in ways that improve soil quality and benefit the environment.

### Oceanic Processes

**Marine Microbial Photosynthesis.** Phytoplankton (microscopic marine plants) and photosynthetic bacteria convert dissolved CO<sub>2</sub> into organic compounds in surface waters. By reducing the partial pressure of CO<sub>2</sub> in the upper ocean, photosynthetic marine microbes enhance the oceans’ physical absorption of CO<sub>2</sub> from the atmosphere. Without phytoplankton photosynthesis, atmospheric CO<sub>2</sub> concentration would be 150 to 200 ppmv higher (Laws et al. 2000). Large oscillations in phytoplankton abundance, therefore, significantly affect the oceans’ ability to take up atmospheric CO<sub>2</sub>. Using metagenomics and other cultivation-independent techniques, scientists are just beginning to understand the composition of microbial communities dominating primary production in oceans. Differences in functional potentials of various photosynthetic microbes remain poorly understood, and predicting the effects of climate change on microbial communities and the marine carbon cycle is difficult.

**Biological Pump.** Although most organic matter produced in surface waters is consumed by heterotrophic microorganisms and other forms of marine life and then returned to the atmosphere as CO<sub>2</sub>, carbon in the form of plankton, fecal pellets, calcium carbonate shells, and dead cells, for example, sinks to the deep ocean. Carbon in the deep ocean is effectively sequestered because it can remain there for thousands to millions of years due to the slow vertical mixing of ocean water. The process that results in transferring organic carbon into the deep ocean and sediments is known as the biological pump. The percentage of photosynthetically fixed carbon that is sequestered by the biological pump is difficult to measure and varies widely among different marine environments. Predicting the magnitude of future changes in oceanic carbon uptake (Falkowski et al. 2000) requires understanding factors controlling the efficiency of the biological pump.

**Processing of Photosynthetically Fixed Carbon.** The fate of organic carbon in marine systems is governed largely by microbial heterotrophs that are responsible for most carbon transformation, solubilization, and subsequent remineralization occurring in the water column. Despite microbes’ crucial role in mediating these processes, only limited information is available regarding the identity of organisms and key genes and proteins involved in degradation of organic matter, as well as the relative degradation rates of various types of compounds.