# Chapter 1. What is the Carbon Cycle and Why Do We Care?

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## WHY A REPORT ON THE CARBON CYCLE?

The concept of a *carbon budget* or *carbon cycle* is unfamiliar to many decision makers and other citizens. We are familiar with a *water cycle*, where precipitation falls on the earth to supply water bodies and evaporation returns water vapor to the earth's clouds, which then renew the cycle through precipitation. Similarly, carbon—a fundamental requirement for life on earth—cycles through exchanges between pools of carbon on and near the earth's surface (mainly in plants and soils), in the atmosphere, and in water and sediments in the ocean. Stated in oversimplified terms, plants consume carbon dioxide ($CO_2$) from the atmosphere through photosynthesis and create sugars and other carbohydrates, which animals and humans use for food, shelter and energy to sustain life. Emissions from plants, other natural systems, and human activities return carbon to the atmosphere, which renews the cycle (Fig. 1-1).

**Figure 1-1. The global carbon cycle.** Carbon cycles through pools or reservoirs of carbon on land, in the ocean, and in sedimentary rock formations over daily, seasonal, annual, millennial and geological time scales. See the accompanying text box.

All of the components of this cycle—the atmosphere, the terrestrial vegetation, soils, freshwater lakes and rivers, the ocean, and geological sediments—are reservoirs of carbon. As carbon cycles through the system, it is exchanged between reservoirs, transferred from one to the next, with exchanges often in both directions. The carbon *budget* is an accounting of the balance of exchanges of carbon among the reservoirs: how much carbon is stored in a reservoir at a particular time, how much is coming in from other reservoirs, and how much is going out. When the inputs to a reservoir (the sources) exceed the outputs (the sinks), the amount of carbon in the reservoir increases. The myriad physical, chemical, and biological processes that transfer carbon among reservoirs, and transform carbon among its various molecular forms during those transfers, are responsible for the cycling of carbon through reservoirs. That cycling determines the balance of the carbon budget observed at any particular time. Examining the carbon budget not only reveals whether the budget is in balance, and if it is unbalanced can provide insights about why such a condition exists and how it might be managed. Currently, the global carbon budget is out of balance, and human use of coal, petroleum, and natural gas to fuel economies is primarily responsible (IPCC, 2001). Ongoing tropical deforestation also contributes, transferring carbon from plants and soils to the atmosphere as carbon dioxide (Houghton, 1999).

If vast quantities of water had been trapped underground for millennia and then, in recent centuries, released to trigger unprecedented rates of evaporation—and thus significant changes in cloud formation and precipitation patterns—there might be concerns about possible imbalances in the water cycle. Although this has not happened for water, it has happened for carbon. Over the millennia, vast quantities of carbon were stored in residues from dead plant and animal life that sank into the earth and became fossilized. With the expansion of the Industrial Revolution in the 19th and 20th centuries, human societies found that these fossils had great value as energy sources for economic growth; and the 20th century saw a dramatic rise in the combustion of these "fossil fuels" (e.g., coal, petroleum, and natural gas), releasing into the atmosphere over *decades* quantities of carbon that had been stored in the earth system over *millennia*. During this same time, forests that had once absorbed very large quantities of carbon dioxide each year shrank in their extent, and continue to do so in tropical regions.

It is not surprising, then, that measurements of carbon dioxide and other carbon compounds in the earth's atmosphere, such as methane, have shown steady increases in concentrations. This fact, together with patterns of human activity that continue trends in fossil fuel use and deforestation, raises concerns about imbalances in the carbon cycle and their implications.

## The Carbon Cycle and Climate Change

Most of the carbon in the earth's atmosphere is in the form of carbon dioxide and methane ($CH_4$). Both carbon dioxide and methane are important "greenhouse gases." Along with water vapor, and other "radiatively active" gases in the atmosphere, they absorb heat radiated from the earth's surface, heat that would otherwise be lost into space. As a result, these gases help warm the earth's atmosphere. Rising concentrations of atmospheric carbon dioxide and other greenhouse gases can alter the earth's radiant energy balance. The earth's energy budget determines the global circulation of heat and water through the atmosphere and the patterns of temperature and precipitation we experience as weather and climate. Thus, the human disturbance of the earth's global carbon cycle during the Industrial era and the resulting imbalance in the earth's carbon budget and buildup of carbon dioxide in the atmosphere have consequences for climate and climate change. According to the Strategic Plan of the U.S. Climate Change Science Program, carbon dioxide is the largest single forcing agent of climate change (CCSP, 2003).

In addition to the relationship between climate change and atmospheric carbon dioxide as a greenhouse gas, research is beginning to reveal the feedbacks between a changing carbon cycle and changing climate and what that implies for future climate change. Simulations with climate models that include an interactive global carbon cycle indicate a positive feedback between climate change and atmospheric carbon dioxide concentrations., The magnitude of the feedback varies considerably among models; but in all cases, future atmospheric carbon dioxide concentrations are higher and temperature increases are larger in the coupled climate-carbon cycle simulations than in simulations without the coupling and feedback between climate change and changes in the carbon cycle (Friedlingstein *et al*., 2006). The research is in its early stages, but 8 of the 11 models in a recent comparison among models (Friedlingstein *et al*., 2006) attributed most of the feedback to changes in land carbon, with the majority locating those changes in the Tropics. Differences among models in almost every aspect of plant and soil response to climate were responsible for the differences in model results, including plant growth in response to atmospheric carbon dioxide concentrations and climate and accelerated decomposition of dead organic matter in response to warmer temperatures.

Invariably, any options or actions to prevent, minimize, or forestall future climate change will require management of the carbon cycle and concentrations of carbon dioxide in the atmosphere. That management involves both reducing sources of atmospheric carbon dioxide such as the combustion of fossil fuels and enhancing sinks such as uptake and storage or sequestration in vegetation and soils. In either case, the formulation of options by decision makers and successful management of the earth's carbon budget requires solid scientific understanding of the carbon cycle and the "ability to account for all carbon stocks, fluxes, and changes and to distinguish the effects of human actions from those of natural system variability" (CCSP, 2003). In short, because people care about the potential consequences of global climate change, they also necessarily care about the carbon cycle, the atmospheric imbalance in the carbon budget, and the balance between sources and sinks of atmospheric carbon on land and in the ocean.

## Other Implications of an Imbalance in the Carbon Budget

We do not yet have a full understanding of the consequences of an unbalanced carbon budget with carbon accumulating in the atmosphere as carbon dioxide and methane, but we do know that they extend beyond climate change alone. Experimental studies, for example, tell us that, for many plant species, rates of photosynthesis often increase in response to elevated concentrations of carbon dioxide, thus potentially increasing plant growth and even agricultural crop yields in the future. There is, however, considerable uncertainty about whether such "$CO_2$ fertilization" will continue into the future with prolonged exposure to elevated carbon dioxide; and, of course, its potential beneficial effects on plants presume climatic conditions that are also favorable to plant and crop growth.

It is also increasingly evident that atmospheric carbon dioxide concentrations are responsible for increased acidity of the surface ocean (Caldeira and Wickett, 2003), with potentially dire future consequences for corals and other marine organisms that build their skeletons and shells from calcium carbonate. Ocean acidification is a powerful reason, in addition to climate change, to care about the carbon cycle and the accumulation of carbon dioxide in the atmosphere (Orr *et al*., 2005).

It is clear that we need to appreciate the importance of the earth's carbon cycle, its implications for our well-being in North America, and the challenge of clarifying what we know versus what we do not know about the carbon cycle. The reason is that any sustained imbalance in the earth's carbon cycle could be serious business indeed for North America, as it could be for any other part of the world.

## Why the Carbon Budget of North America?

The continent of North America has been identified as both a significant source and a significant sink of atmospheric carbon dioxide (Wofsy and Harriss, 2002). More than a quarter (27%) of global carbon emissions from the combination of fossil fuel and cement manufacturing are attributable to North America (United States, Canada, and Mexico) (Marland *et al*., 2003). North American plants remove carbon dioxide from the atmosphere and store it as carbon in plant biomass and soil organic matter, mitigating to some degree the anthropogenic sources. The magnitude of the "North American sink" has been estimated at anywhere from less than 100 Mt C $yr^{-1}$ to slightly more than 2000 Mt C $y^{-1}$ (Turner *et al*., 1995; Fan *et al*., 1998), with a value near 350 to 750 Mt C $yr^{-1}$ perhaps most likely (Houghton *et al*., 1999; Goodale *et al*., 2002; Gurney *et al*., 2002). In Chapter 3 of this report the sink is estimated to be 592 Mt C $yr^{-1}$. The North American sink is thus a substantial, if highly uncertain fraction, from 15% to essentially 100%, of the extra-tropical Northern Hemisphere terrestrial sink estimated to be in the range of 600 to 2300 Mt C $yr^{-1}$ during the 1980s (IPCC, 2001). It is also a reasonably large fraction (perhaps near 30%) of the global terrestrial sink estimated at 1900 Mt C $yr^{-1}$ for the 1980s (but with a range of uncertainty from a large sink of 3800 Mt C $yr^{-1}$ to a small source of 300 Mt C $yr^{-1}$ (IPCC, 2001). The global terrestrial sink is responsible for about a quarter to a half of the carbon added to the atmosphere by human actions that was subsequently transferred to oceans and land by carbon cycle processes. This is carbon that did not contribute to the accumulation and increase of carbon dioxide in the atmosphere. Global atmospheric carbon concentrations would be substantially higher than they are without the partially mitigating influence of the sink in North America.

Some mechanisms that might be responsible for the North American terrestrial sink are reasonably well known. These mechanisms include, but are not limited to, the re-growth of forests following abandonment of agriculture, changes in fire and other disturbance regimes, historical climate change, and fertilization of ecosystem production by nitrogen deposition and elevated atmospheric carbon dioxide (Dilling *et al*., 2003). Recent studies have indicated that some of these processes are likely more important than others for the current North American carbon sink, with regrowth of forests on former agricultural generally considered to be a major contributor, and with perhaps a significant contribution from enhanced plant growth in response to higher concentrations of atmospheric carbon dioxide ($CO_2$ fertilization) (Caspersen *et al*., 2000; Schimel *et al*., 2000; Houghton 2002). But significant uncertainties remain (Caspersen *et al*., 2000; Schimel *et al*., 2000; Houghton 2002), with some arguing that even the experimental evidence for $CO_2$ fertilization is equivocal at the larger spatial scales necessary for a significant terrestrial sink (e.g., Nowak *et al*., 2004; Friedlingstein *et al*., 2006). The future of the current North American terrestrial sink is highly uncertain, and it depends on which mechanisms are the dominant drivers now and in the future.

Estimates of coastal carbon cycling and input of carbon from the land are equally uncertain (JGOFS, 2001). Coastal processes are also difficult to parameterize in global carbon cycle models, which are often used to derive best-guess estimates for regional carbon budgets (JGOFS, 2001). It is very important to quantify carbon fluxes in coastal margins of the area adjacent to the North American continent, lest regional budgets of carbon on land be mis-attributed.

Whether as source or sink, North America is a major player in the global carbon cycle. The scientific understanding of the global carbon cycle required for successful carbon management strategies and by decision makers searching for options to stabilize or mitigate concentrations of greenhouse gases in the atmosphere (CCSP, 2003) requires an understanding of the North American carbon budget.

In the absence of explicit and specific carbon management targets it is difficult to address the question of just how well, with what precision, the North American carbon budget must be known to achieve carbon management goals. It is clear, however, that a terrestrial sink generated by “natural” processes is an ecosystem service worth billions of dollars if purchased or realized through direct human economic and technological intervention (Pep Canadell, personal communication, 2006). Its existence will influence carbon management decision making, and it is important that its magnitude and its dynamics be well understood.

It is particularly important to understand the likely future behavior of the carbon cycle, including terrestrial and oceanic sources and sinks. Decisions made about future carbon management with expectations of the future behavior of the carbon cycle that proved to be significantly in error, could be costly. For example, the response of the carbon cycle to future climate-carbon feedbacks could change the strength of terrestrial sinks and put further pressure on emission reductions to achieve, for example, atmospheric stabilization targets (Pep Canadell, personal communication, 2006). The future can't be known, but understanding it's past and present will increase confidence in projections of future carbon cycle behavior for appropriate consideration by decision makers.

## CARBON CYCLE SCIENCE IN SUPPORT OF CARBON MANAGMENT DECISIONS

Beyond understanding the science of the North American carbon budget and its drivers, increasing attention is now being given to deliberate management strategies for carbon (DOE, 1997, Hoffert *et al.*, 2002; Dilling *et al.*, 2003). Carbon management is now being considered at a variety of scales in North America. There are tremendous opportunities for carbon cycle science to improve decision-making in this arena, whether in reducing carbon emissions from the use of fossil fuels, or in managing terrestrial carbon sinks. Many decisions in government, business, and everyday life are connected with the carbon cycle. They can relate to *driving forces* behind changes in the carbon cycle (such as consumption of fossil fuels) and strategies for managing them and/or *impacts* of changes in the carbon cycle (such as climate change or ocean acidification) and responses to reduce their severity. Carbon cycle science can help to inform these decisions by providing timely and reliable information about facts, processes, relationships, and levels of confidence.

In seeking ways to more effectively use scientific information in decision-making, we must pay particular attention to the importance of developing constructive scientist–stakeholder interactions. Studies of these interactions all indicate that neither scientific research nor assessments can be assumed to be relevant to the needs of decision-makers if conducted in isolation from the context of those users needs (Cash and Clark, 2001; Cash *et al*., 2003; Dilling *et al*., 2003; Parson, 2003). Carbon cycle science's support of decision-making is more likely to be effective if the science is connected with communication structures that are considered by both scientists and users to be legitimate and credible. Well designed scientific assessments can be one of these effective communication media.

The U.S. climate and carbon research community, and a diverse range of stakeholders, recognize the need for an integrated synthesis and assessment focused on North America to (a) summarize what is known and what is known to be unknown, documenting the maturity as well as the uncertainty of this knowledge; (b) convey this information among scientists and to the larger community; and (c) ensure that our studies are addressing the questions of concern to society and decision-making communities. As the most comprehensive treatment to date of carbon cycle facts, directions, and issues for North America, incorporating stakeholder interactions throughout, this report, the *First State of the Carbon Cycle Report (SOCCR)*, focused on *The North American Carbon Budget and Implications for the Global Carbon Cycle* is intended as a step in that direction.

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**The Global Carbon Cycle**

The burning of fossil fuels transfers carbon from geological reservoirs of coal, oil and gas and releases carbon dioxide into the atmosphere. Tropical deforestation and other changes in land-use also release carbon to the atmosphere as vegetation is burned and dead material decays. Photosynthesis transfers carbon dioxide from the atmosphere and the carbon is stored in wood and other plant tissues. The respiration that accompanies plant metabolism transfers some of the carbon back to the atmosphere as carbon dioxide. When plants die, their decay also releases carbon dioxide to the atmosphere. A fraction of the dead organic material is resistance to decay and that carbon accumulates in the soil. Chemical and physical processes are responsible for the exchange of carbon dioxide across the sea surface. The small difference between the flux in to and out of the surface ocean is responsible for net uptake of carbon dioxide by the ocean. Phytoplankton, small plants floating in the surface ocean, use carbon dissolved in the water to build tissue and calcium carbonate shells. When they die, they begin to sink and decay. As they decay, most of the carbon is redissolved into the surface water, but a fraction sinks into the deeper ocean, the so-called “biological pump”, eventually reaching he ocean sediments. Currents within the ocean also circulate carbon from surface waters to Deep Ocean and back. Carbon accumulated in soils and ocean sediments millions of years of ago was slowly transformed to produce the geological reservoirs of today’s fossil fuels.

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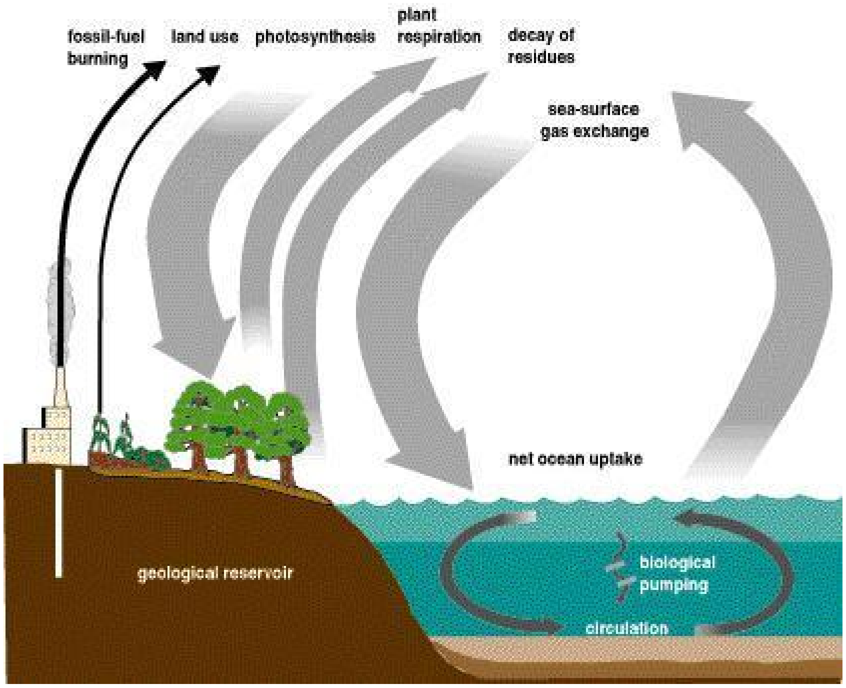


**Figure 1-1. The global carbon cycle.** Carbon cycles through pools or reservoirs of carbon on land, in the ocean, and in sedimentary rock formations over daily, seasonal, annual, millennial and geological time scales. See the accompanying text box.