CHAPTER 1

What Is the Carbon Cycle and Why Care?

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1.1 WHY A REPORT ON THE CARBON CYCLE?

The concept of a carbon cycle is probably unfamiliar to most people other than scientists and some decision makers in the public and private sectors. More familiar is the water cycle, where precipitation falls on the earth to supply water bodies and evaporation returns water vapor to the clouds, which then renew the cycle through precipitation. In an analogous way, carbon—a fundamental requirement for life on Earth—cycles through exchanges among stores (or reservoirs) of carbon on and near the Earth's surface (mainly in plants and soils), in the atmosphere (mainly as gases), and in water and sediments in the ocean. Stated in oversimplified terms, plants take up 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 (Figure 1.1).

All of the components of this cycle—the atmosphere, the terrestrial vegetation, soils, freshwater lakes and rivers, the ocean, and geological sediments—are reservoirs (stores) 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 is increased. 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. Quantifying the carbon budget over time can reveal whether the budget is or is not in balance (carbon accumulating in a reservoir would indicate an imbalance). If found to be out of balance, this quantification can provide understanding about why such a condition exists (for example, which sources exceed which sinks over what periods) (Sabine *et al*., 2004, Chapter 2 this report). If the imbalance is deemed undesirable, the understanding of source and sinks can provide clues into how it might be managed (for example, which sinks are large relative to sources and might, if managed, provide leverage on changes in a reservoir) (Caldeira *et al*., 2004; Chapter 4 this report). The global carbon budget is currently out of balance, with carbon accumulating in the form of CO_2 and methane (CH_4) in the atmosphere since the preindustrial era (*circa* 1750). Human use of coal, petroleum, and natural gas, combined with agriculture and other land-use change is primarily responsible. Documented by the Intergovernmental Panel on Climate Change for the 1990s (IPCC, 2001, p. 4), these trends continue in the early twenty-first century (Keeling and Whorf, 2005; Marland *et al*., 2006).

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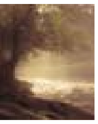
The history of the Earth's carbon balance as reflected in changes in atmospheric CO_2 concentration can be reconstructed from geological records, geochemical reconstructions, measurements on air bubbles trapped in glacial ice, and in recent decades, direct measurements of the atmosphere. Over the millennia, tens and hundreds of millions of



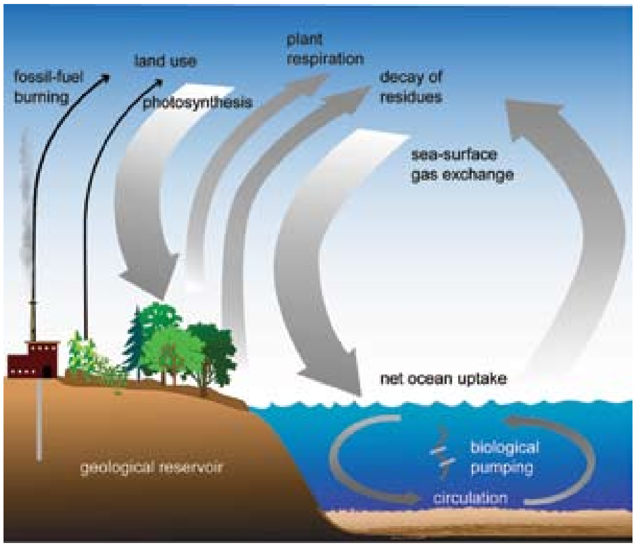


Figure 1.1 The Earth's carbon cycle. Carbon cycles through pools or reservoirs of carbon on land, in the ocean, and in sedimentary rock formations over daily, seasonal, annual, millennial, and geological time scales. See the accompanying text box. Figure adapted from http://www.esd.ornl.gov/iab/iab2-2.htm.

BOX 1.1: The Earth's Carbon Cycle

The burning of fossil fuels transfers carbon from geological reservoirs of coal, oil, and gas and releases carbon dioxide (CO_2) 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 CO_2 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 CO_2. When plants die, their decay also releases CO_2 to the atmosphere. A fraction of the dead organic material is resistant to decay and that carbon accumulates in the soil. Chemical and physical processes are responsible for the exchange of CO_2 across the sea surface. The small difference between the flux into and out of the surface ocean is responsible for net uptake of CO_2 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 the ocean sediments. Currents within the ocean also circulate carbon from surface waters to the 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. For a more detailed, quantitative description, see Prentice *et al.* (2001), Houghton (2003), Sundquist and Visser (2003), Sabine *et al.* (2004), and Chapter 2 of this report.

years ago, vast quantities of carbon were stored in residues from dead plant and animal life that sank into the earth and became fossilized. On these time scales, small imbalances in the carbon cycle and geological processes, acting over millions of years, produced large but slow changes in atmospheric CO_2 concentrations of greater than 3000 parts per million (ppm) over periods of 150-200 million years (Prentice *et al.*, 2001). By perhaps 20 million year ago, atmospheric CO_2 concentrations were less than 300 ppm (Prentice *et al.*, 2001). Subsequently, imbalances in the carbon cycle linked with climate variations, especially the large glacial-interglacial cycles of the last 420,000 years, resulted in changes of approximately 100 ppm over periods of 50-75 thousand years (Prentice *et al.*, 2001; Sabine *et al.*, 2004). During the current interglacial climate, for at least the last 11,000 years, variations in atmospheric CO_2, also likely climate driven, were less than 20 ppm (Joos and Prentice, 2004). For 800-1000 years prior to the Industrial Revolution of the 1700s and 1800s, atmospheric CO_2 concentrations varied by less than 10 ppm (Prentice *et al.*, 2001).

With the advent of the steam engine, the internal combustion engine, and other technological and economic elements of the Industrial Revolution, human societies found that the fossilized carbon formed hundreds of millions of years ago had great value as energy sources for economic growth. The 1800s and 1900s 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. These fossil-fuel emissions combined with and soon exceeded (*circa* 1910) the CO_2 emissions from burning and decomposition of dead plant material that accompanied clearing of forests for agricultural land use (Houghton, 2003).

It is not surprising, then, that measurements of CO_2 in the Earth's atmosphere have shown a steady increase in concentration over the twentieth century (Keeling and Whorf, 2005). The global CO_2 concentration has increased by approximately 100 ppm over the past 200 years, from a preindustrial concentration of 280 ± 10 ppm (Prentice *et al.*, 2001) to a concentration (measured at Mauna Loa, Hawaii) of 369 ppm in 2000 and 377 ppm in 2004 (Keeling and Whorf, 2005). Methane shows a similar pattern, with relatively stable concentrations prior to about 1800 followed by a rapid increase (Ehhalt *et al.*, 2001). Roughly, 20% of CH_4 emissions are from gas released in the extraction and transportation of fossil fuels; the rest is from biological sources including expanding rice and cattle production (Prinn, 2004). Such large increases in atmospheric carbon over such a short period of time relative to historical variations, together with patterns of human activity that will likely continue into the twenty-first century, such as trends in fossil-fuel use and tropical deforestation, raises concerns about imbalances in the carbon cycle and their implications.

1.2 THE CARBON CYCLE AND CLIMATE CHANGE

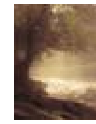
Most of the carbon in the Earth's atmosphere is in the form of CO_2 and CH_4. Both CO_2 and CH_4 are important "greenhouse gases." Along with water vapor and other "radiatively active" gases in the atmosphere, they absorb heat radiated from the Earth's surface, heat that would otherwise be lost into space. As a result, these gases help to warm the Earth's atmosphere. Rising concentrations of atmospheric CO_2 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 atmospheric CO_2 have consequences for climate and climate change. According to the IPCC, CO_2 is the largest single forcing agent of climate change (IPCC, 2001)[1].

In addition to the relationship between climate change and atmospheric CO_2 as a greenhouse gas, research is beginning to reveal the feedbacks between a changing carbon cycle and changing climate, and the associated implications for future climate change. Simulations with climate models that include an interactive global carbon cycle indicate a positive feedback between climate change and atmospheric CO_2 concentrations. The magnitude of the feedback varies considerably among models; but in all cases, future atmospheric CO_2 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 CO_2 concentrations and climate and accelerated decomposition of dead organic matter in response to warmer temperatures.

Changes in temperature, precipitation, and other climate variables also contribute to year-to-year changes in carbon cycling. Nearly all of the biological, chemical, and physical processes responsible for exchange of carbon between atmosphere, land, and ocean are influenced to some degree by climate variables, and both ocean-atmosphere and land-atmosphere exchanges (sources and sinks) show year-to-year variation attributable to variability in climate (Prentice *et al*., 2001; Schaefer *et al*., 2002; Houghton, 2003; Sabine *et al*., 2004; Greenblatt and Sarmiento, 2004; Chapter 2 this report). This variability is believed to be responsible for the large year-to-year differences in the accumulation of CO_2 in the atmosphere; annual changes differ by as much as 3000 to 4000 million metric tons of carbon (Mt C) per year (Prentice *et al*., 2001; Houghton, 2003). Both land and ocean show changes, for example, in apparent response to climate conditions linked to El Niño events, although the variability in the net land-atmosphere exchange is larger (Prentice *et al*., 2001; Houghton, 2003; Sabine *et al*., 2004). Figure 1.2 illustrates this variability, showing for North America year-to-year variation in satellite observations of the annual net transfer of carbon from the atmosphere to plants. Variability of this sort, in both land and ocean, contributes uncertainty to carbon budgeting and may appear as "noise" when attempting to detect "signals" of longer-term climate relevant trends (Sabine *et al*., 2004) or, eventually, signals of effective carbon management.

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 atmospheric CO_2 have consequences for climate and climate change.

Many of the currently proposed options to prevent, minimize, or forestall future climate change will likely require management of the carbon cycle and concentrations of CO_2 in the atmosphere. That management includes both reducing sources, such as the combustion of fossil fuels, and enhancing sinks, such as uptake and storage (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).



[1] Methane is also an important contributor (IPCC, 2001). However, CH4 and other non-CO2 carbon gases are not typically included in global carbon budgets because their sources and sinks are not well understood (Sabine *et al*., 2004). For this reason, and to manage scope and focus, we too follow that convention and this report is limited primarily to the carbon cycle and carbon budget of North America as it influences and is influenced by atmospheric CO2. Methane is discussed in individual chapters where appropriate, but the report makes no effort to provide a comprehensive synthesis and assessment of CH4 as part of the North American carbon budget. Similarly we provide no comprehensive treatment of black carbon, isoprene, or other volatile organic carbon compounds that represent a small fraction of global or continental carbon budgets.

So, why care about the carbon cycle? In short, because people care about the potential consequences of global climate change, they also, necessarily, care about the carbon cycle and the balance between carbon sources and sinks, natural and human, which determine the budget imbalance and accumulation of carbon in the atmosphere as CO_2.

1.3 OTHER IMPLICATIONS OF AN IMBALANCE IN THE CARBON BUDGET

The consequences of an unbalanced carbon budget with carbon accumulating in the atmosphere as CO_2 and CH_4 are not completely understood, but it is known that they extend beyond climate change alone. Experimental studies, for example, show that for many plant species, rates of photosynthesis often increase in response to elevated concentrations of CO_2 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 CO_2; 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 CO_2 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 CO_2 in the atmosphere (Orr *et al*., 2005).

1.4 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 CO_2 (IPCC, 2001; Pacala *et al*., 2001; Goodale *et al*., 2002; Gurney *et al*., 2002; EIA, 2005). More than a quarter (27%) of global carbon emissions, from the combination of fossil-fuel burning and cement manufacturing, are attributable to North America (United States, Canada, and Mexico) (Marland *et al*., 2003). North American plants remove CO_2 from the atmosphere and store it as carbon in plant biomass and soil organic matter, mitigating to some degree the human-caused (anthropogenic) sources. The magnitude of the "North American sink" has been previously estimated at anywhere from less than 100 Mt C per year to slightly more than 2000 Mt C per year (Turner *et al*., 1995; Fan *et al*., 1998), with a value near 350 to 750 Mt C per year most likely (Houghton *et al*., 1999; Goodale *et al*., 2002; Gurney *et al*., 2002). 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 per year during the 1980s (Prentice *et al*., 2001). It is also a reasonably large fraction (perhaps near 30%) of the global terrestrial sink estimated at 1900 Mt C per year for the 1980s (but with a range of uncertainty from a large sink of 3800 Mt C per year to a small source of 300 Mt C per year (Prentice *et al*., 2001). The global terrestrial sink absorbs approximately one quarter of the carbon added to the atmosphere by human activities, but with uncertainties linked to the uncertainties in the size of that sink. Global atmospheric carbon concentrations would be substantially higher than they are without the partially mitigating influence of the sink in North America. However, estimates of that sink vary widely, and it needs to be better quantified.

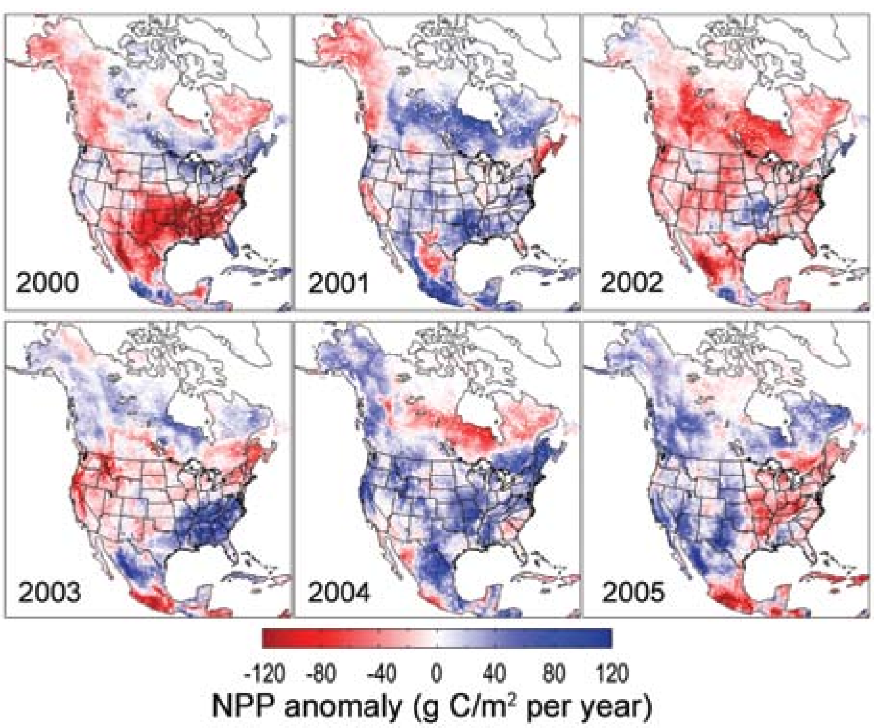


Figure 1.2 Variability in net primary production (NPP) for North America from 2000-2005. Values are the deviation from 6-year average annual NPP estimated by the MOD17 1-km resolution data product from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the National Aeronautics and Space Administration (NASA) Terra and Aqua satellites. Blue indicates regions where that year's NPP, the net carbon fixed by vegetation from the atmosphere, was greater than average; red indicates where annual NPP was less than the average. See Running *et al.* (2004) for further information on the MODIS NPP product. Figure courtesy of Dr. Steven W. Running, University of Montana.

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 regrowth 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 CO_2 (Dilling *et al*., 2003; Foley *et al*., 2004). 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 land generally considered to be a major contributor, and with, perhaps, a significant contribution from enhanced plant growth in response to higher concentrations of atmospheric CO_2 (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 (Liu *et al*., 2000). 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 (Liu *et al*., 2000). 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 misattributed.

North America is a major player in the global carbon cycle, in terms of both sources and sinks. Accordingly, understanding the carbon budget of North America is a necessary part of understanding the global carbon cycle. Such understanding is helpful for successful carbon management strategies to mitigate fossil-fuel emissions or stabilize concentrations of greenhouse gases in the atmosphere. Moreover, a large North American terrestrial sink generated by "natural" processes is an ecosystem service that would be valued at billions of dollars if purchased or realized through direct human economic and technological intervention. Its existence will likely influence carbon-management decision making, and it is important that its magnitude and its dynamics be well understood (Kirschbaum and Cowie, 2004; Canadell *et al*., 2007).

More than a quarter (27%) of global carbon emissions are attributable to North America.

It is particularly important to understand the likely future behavior of carbon in North America, 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, future climate-carbon feedbacks could change the strength of terrestrial sinks and put further pressure on emission reductions to achieve atmospheric stabilization targets (Jones *et al*., 2006; Canadell *et al*., 2007). The future cannot be known, but understanding the current and historical carbon cycle will increase confidence in projections for appropriate consideration by decision makers.

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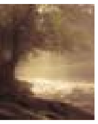
1.5 CARBON CYCLE SCIENCE IN SUPPORT OF CARBON MANAGEMENT DECISIONS

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 use scientific information more effectively 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 connected with communication structures is considered by both scientists and users to be legitimate and credible. Well-designed scientific assessments can be one of these effective communication media.

The climate and carbon research community of North America, 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 to 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 synthesis to date of carbon cycle knowledge and trends for North America, incorporating stakeholder interactions throughout its production[2], 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.

[2] A discussion of stakeholder participation in the production of this report can be found in the *Preface* of this report.