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

An Introduction to the Purpose, Scope, and Structure of the State of the Carbon Cycle Report (SOCCR)

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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 (a) carbon-based life on and near the earth's surface, (b) carbon in the earth's atmosphere, and (c) water in the ocean. Stated in oversimplified terms, plants consume carbon dioxide from the atmosphere through photosynthesis and create sugars and other carbohydrates, which animals and humans use for food and shelter 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. Reservoirs (in black) are gigatons [1 Gt = one billion (1×10^9) metric tons] of carbon, and exchanges between reservoirs (in purple) are Gt carbon per year. *Illustration courtesy NASA Earth Science Enterprise*.

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. 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 that transfer, 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 or imbalance, but also provides insight into causes of any imbalance and steps that might be taken to manage that imbalance. Currently, the global carbon budget is in imbalance; and human use of coal, petroleum, and natural gas to fuel economies is responsible.

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 *millenia*. During this same time, forests that had once absorbed very large quantities of carbon dioxide each year shrank in their extent.

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 (CO_2) 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 research is in its early stages, and 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).

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 and the atmospheric imbalance in the carbon budget.

Other Implications of an Imbalance in the Carbon Budget

We do not yet have a full understanding of the consequences of this imbalance, 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 acidification of the surface ocean, 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.

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 vs 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). The North American sink is thus a substantial fraction, perhaps on the order of 30–60%, of the global terrestrial sink estimated to be in the range of 600 to 2300 Mt C yr^{-1} and primarily in the extra-tropical Northern Hemisphere (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 transferred to oceans and land by carbon cycle processes and thus 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, but significant uncertainties remain (Caspersen *et al.*, 2000; Schimel *et al*., 2000; Houghton 2002). The future of the current North American terrestrial sink is highly uncertain, and it depends on which mechanisms are the dominant drivers.

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.

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. 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.

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, although such support 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.

Perhaps the most widely studied examples of scientist–stakeholder communication and dialogue have occurred through various types of scientific assessments. For example, Cash and Clark (2001) and Cash *et al.* (2003) found that the most effective[1] scientific assessments generally shared three interdependent characteristics, which they termed credibility, saliency, and legitimacy. Credibility is obviously essential if a scientific assessment is to be viewed as technically authoritative. The credibility of an assessment depends on the scientific scope and rigor of the process and on the scientific stature of its participants (Parson, 2003).

[1] The effectiveness of scientific syntheses and assessments is evaluated using a variety of criteria, including effects on policies, management options, research agendas, and attitudes of key constituencies (Cash and Clark, 2001; Parson 2003). These are not the only possible effectiveness criteria, but they provide an appropriate emphasis on the effectiveness of scientifically credible information that can be easily communicated to stakeholders and that they find useful for policy and management.

Saliency, according to Cash and Clark, is the extent to which an assessment is perceived as relevant and useful to stakeholders. Ensuring saliency requires early and ongoing dialogue with stakeholders to make sure that the questions posed within the scientific community are also important to the stakeholder community, and to educate the stakeholder community about the importance of scientific issues that they might otherwise overlook.

Cash and Clark (2001) defined legitimacy as the "perceived fairness of the assessment process." The legitimacy of a scientific assessment requires not only the contributions of scientific experts who represent a range of technical viewpoints, but also the substantive involvement of stakeholder representatives to ensure that the assessment is perceived as fair by their constituencies.

A common conclusion in analyses of scientific assessments is that the initial design and context are critically important (Cash and Clark, 2001; Farrell *et al.*, 2001; Parson 2003). The community and institutional mandate for an assessment have a strong influence on the eventual success of the process. The initial "framing" of the issues and questions to be addressed affects many decisions about the organization of the assessment, communication among participants, prioritization of goals, and ultimate effectiveness (Farrell *et al.*, 2001). The framing process requires great care because it may predetermine not only *who* gets to pose the questions, but also *how* the questions are posed.

How the assessment is delivered is as important as how it is defined. A potential pitfall in scientific assessment is to focus solely on producing a written report of findings, without understanding the importance of ongoing communication and social interaction that are critical for effective outcomes (Cash and Clark, 2001). Our proposed approach pays considerable attention to the ongoing process required to produce the SAP 2.2, with the explicit goal of ensuring that the SAP 2.2 is not only scientifically credible but also easily accessible, credible, and relevant to decision makers and other stakeholders. Transparency of the process will be a high priority through all stages.

Analysis of previous scientific assessments has emphasized that credibility, saliency, and legitimacy are inter-connected. As Parson (2003) put it, "Assessments that command little attention or respect by virtue of the collective stature of their participants; that draw no clear scientific judgments or conclusions about present knowledge except that more research is needed; that present no cogent new ways to understand the issue; and whose reports are both useless to scientists and inaccessible to lay persons, can expect to have no influence on policy, however high the quality of their work on other dimensions."

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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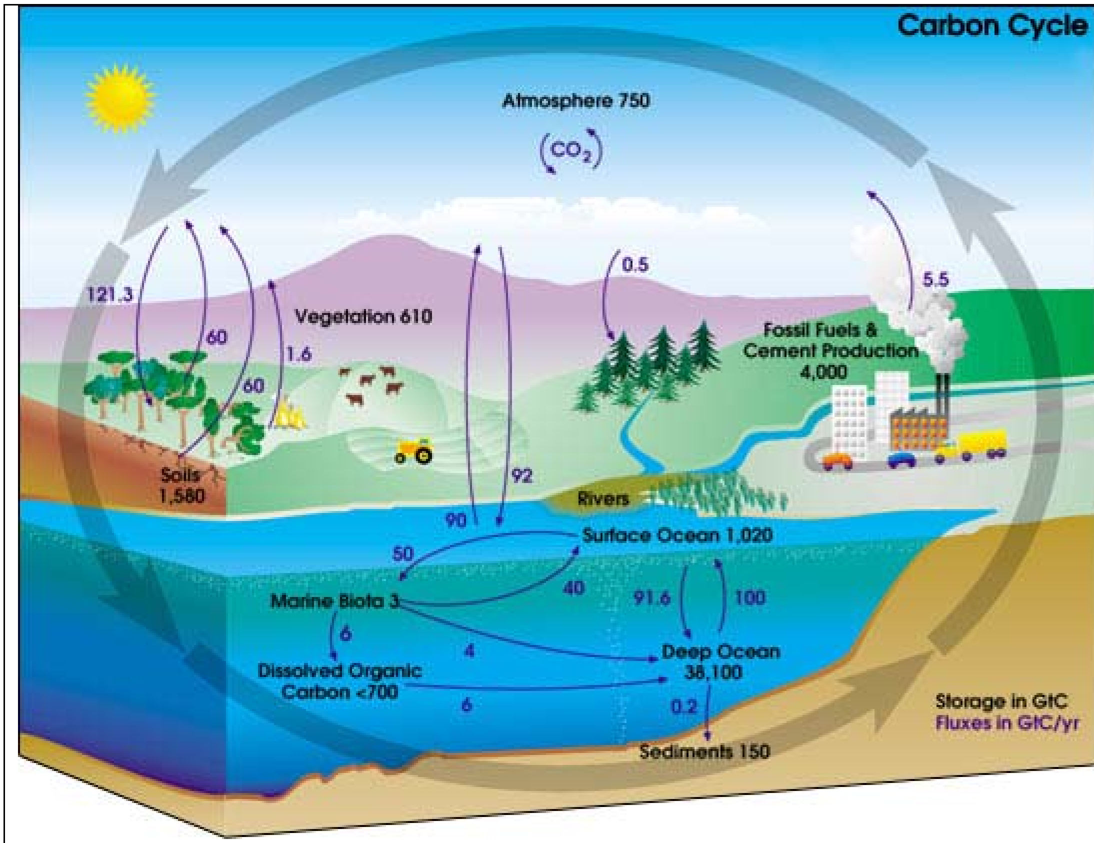

Figure 1-1. The global carbon cycle. Reservoirs (in black) are gigatons [1 Gt = one billion (1×10^9) metric tons] of carbon, and exchanges between reservoirs (in purple) are Gt carbon per year. *Illustration courtesy NASA Earth Science Enterprise*.

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