CHAPTER 1

What Is the Carbon Cycle and Why Care?

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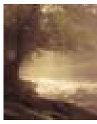


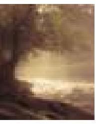
1.1 WHY A REPORT ON THE CARBON CYCLE?

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).

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).

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



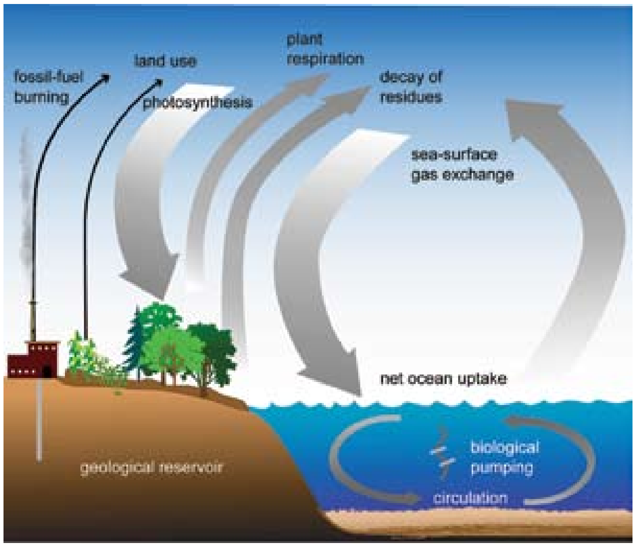


Figure 1.1 The Earth's carbon cycle. Carbon cycles through pools or reservoirs of carbon on land, in the ocean, and in sedimentary rock formations over daily, seasonal, annual, millennial, and geological time scales. See the accompanying text box. Figure adapted from http://www.esd.ornl.gov/iab/iab2-2.htm.

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).

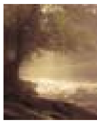
With the advent of the steam engine, the internal combustion engine, and other technological and economic elements of the Industrial Revolution, human societies found that the fossilized carbon formed hundreds of millions of years ago had great value as energy sources for economic growth. The 1800s and 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).

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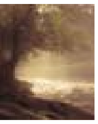
[1] Methane is also an important contributor (IPCC, 2001). However, CH4 and other non-CO2 carbon gases are not typically included in global carbon budgets because their sources and sinks are not well understood (Sabine *et al*., 2004). For this reason, and to manage scope and focus, we too follow that 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.

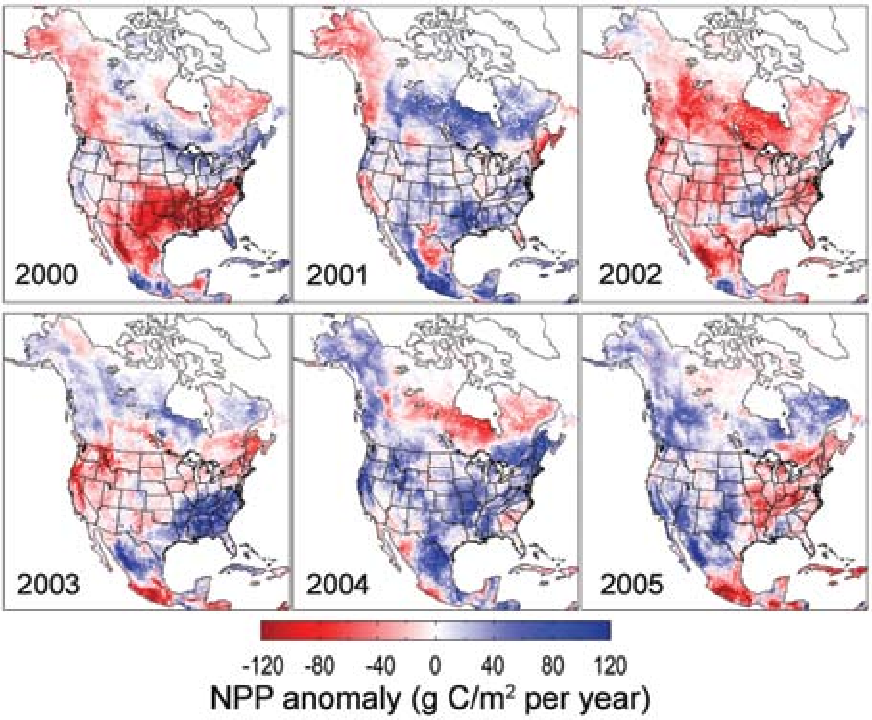


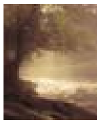
Figure 1.2 Variability in net primary production (NPP) for North America from 2000-2005. Values are the deviation from 6-year average annual NPP estimated by the MOD17 1-km resolution data product from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the National Aeronautics and Space 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.

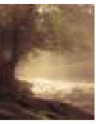


It is particularly important to understand the likely future behavior of carbon in North America, including terrestrial and oceanic sources and sinks. Decisions made about future carbon management with expectations of the future behavior of the carbon cycle that proved to be significantly in error, could 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.

North America is a major player in the global carbon cycle, in terms of both sources and sinks.

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.

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

CHAPTER 2

The Carbon Cycle of North America in a Global Context

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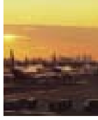
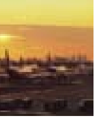


KEY FINDINGS

- Human activity over the last two centuries, including combustion of fossil fuel and clearing of forests, has led to a dramatic increase in the concentration of atmospheric carbon dioxide. Global atmospheric carbon dioxide concentrations have risen by 31% since 1850 and are now higher than they have been for at least 420,000 years.
- North America is responsible for approximately 25% of the emissions produced globally in 2004 by fossil-fuel combustion, with the United States accounting for 86% of the North American total.
- Human-caused emissions (a carbon source) dominate the carbon budget of North America. Largely unmanaged, unintentional processes capture a fraction of this carbon in plants, soils, and other sinks. Currently, these sinks (970 ± 360 million metric tons of carbon (Mt C) per year, based on atmospheric inversion studies, or 530 ± 265 Mt C per year, based on the inventories used in this report) capture approximately 30-50% of the North American emissions, 7-13% of global fossil-fuel emissions, and 30-50% of the global terrestrial sink inferred from global budget analyses and atmospheric inversions.
- While the future trajectory of carbon sinks in North America is uncertain (substantial climate change could convert current sinks into sources), it is clear that the carbon cycle of the next few decades will be dominated by the large sources from fossil-fuel emissions.
- Because North American carbon emissions are at least a quarter of global emissions, a reduction in North American emissions would have global consequences.



2.1 THE GLOBAL CARBON CYCLE

The modern global carbon cycle is a collection of many different kinds of processes, with diverse drivers and dynamics, that transfer carbon among major pools in rocks, fossil fuels, the atmosphere, the oceans, and plants and soils on land (Sabine *et al.*, 2004b) (Figure 2.1). During the last two centuries, human actions, especially the combustion of fossil fuel and the clearing of forests, have altered the global carbon cycle in important ways. Specifically, these actions have led to a rapid, dramatic increase in the concentration of carbon dioxide (CO_2) in the atmosphere (Figure 2.2), changing the radiation balance of the Earth (Hansen *et al.*, 2005), and very likely causing much of the warming observed over the last 50 years (Hegerl et al., 2007). The cause of the recent increase in atmospheric CO_2 is confirmed beyond a reasonable doubt (Prentice, 2001). This does not imply, however, that the other components of the carbon cycle have remained unchanged during this period. In fact, the background, or unmanaged parts, of the carbon cycle have changed dramatically over the past two centuries. The consequence of these changes is that only about 40% ± 15%[1] of the CO_2 emitted to the atmosphere from fossil-fuel combustion and forest clearing has remained there (Sabine *et al.*, 2004b). In essence, human actions have received a large subsidy from the unmanaged parts of the carbon cycle. This subsidy has sequestered, or hidden from the atmosphere, approximately 279 ± 160 billion tons (gigatons [Gt]) of carbon[2].

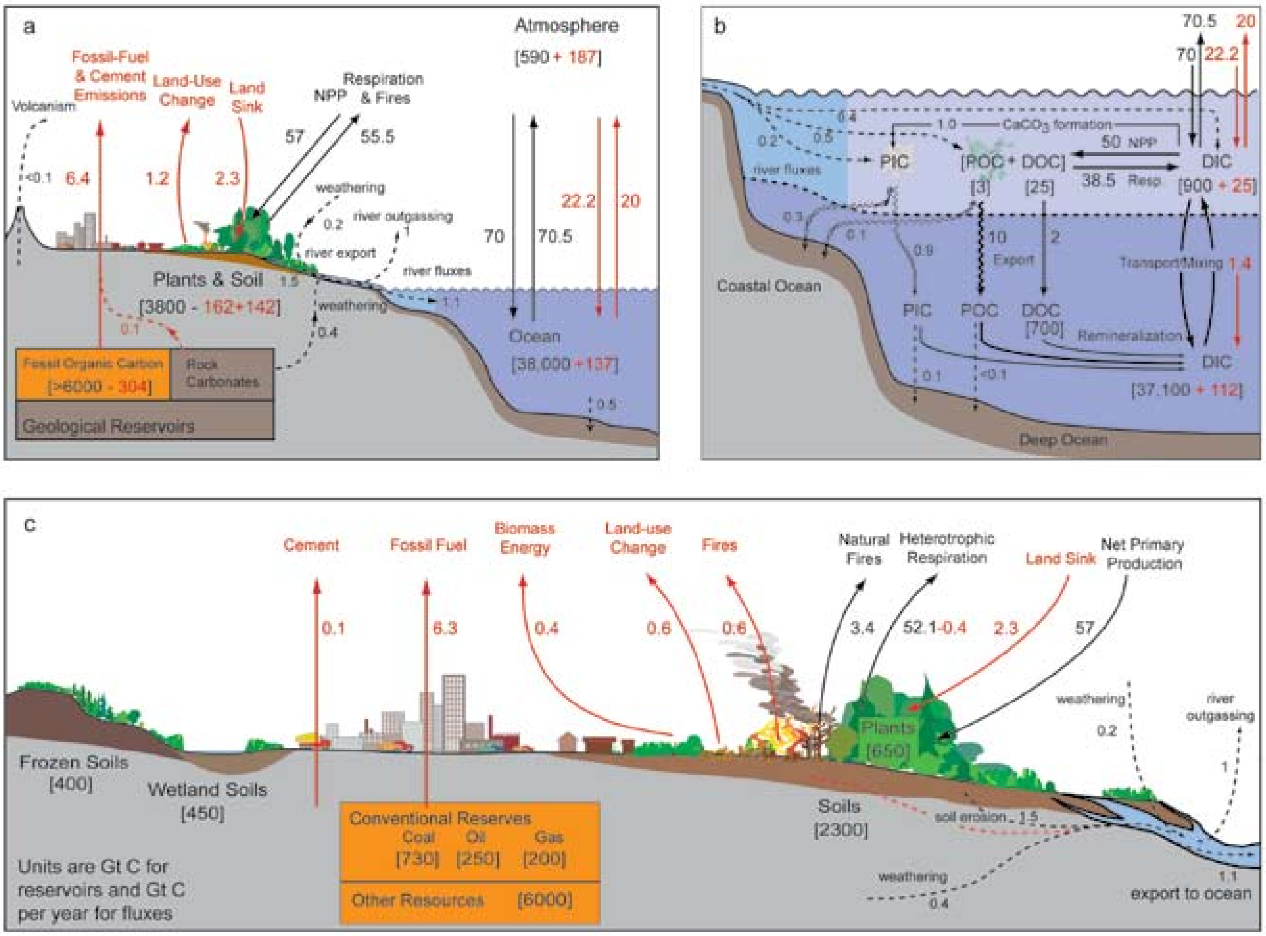


Figure 2.1 Schematic representation of the components of the global carbon cycle. The three panels show (a) the overall cycle, (b) the details of the ocean cycle, and (c) the details of the land cycle. For all panels, carbon stocks are in brackets, and fluxes have no brackets. Stocks and fluxes prior to human-influence are in black. Human-induced perturbations are in red. For stocks, the human-induced perturbations are the cumulative total through 2003. H uman-caused fluxes are means for the 1990s (the most recent available data for some fluxes). Redrawn from Sabine *et al.* (2004b) with updates through 2003 as discussed in the text.

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[1] Most of the uncertainty in this number is due to the approximately 100% uncertainty in carbon lost from forest clearing. This includes uncertainties in areas deforested, in conditions at the time of deforestation, and in the fate following deforestation (Houghton, 1999). Except where otherwise noted, the uncertainty bounds on the numbers in this chapter are expert assessments by the authors of the cited literature, based on synthesizing a wide range of empirical and modeling studies. The details of the approaches to assessing uncertainty are discussed in the literature cited.

[2] Unless specified otherwise, throughout this chapter, the pools and fluxes in the carbon cycle are presented in Gt C [1 Gt = 1 billion tons or 1×10^{15} g]. The mass of CO_2 is greater than the mass of carbon by the ratio of their molecular weights, 44/12 or 3.67 times; 1 km^3 of coal contains approximately 1 Gt C.

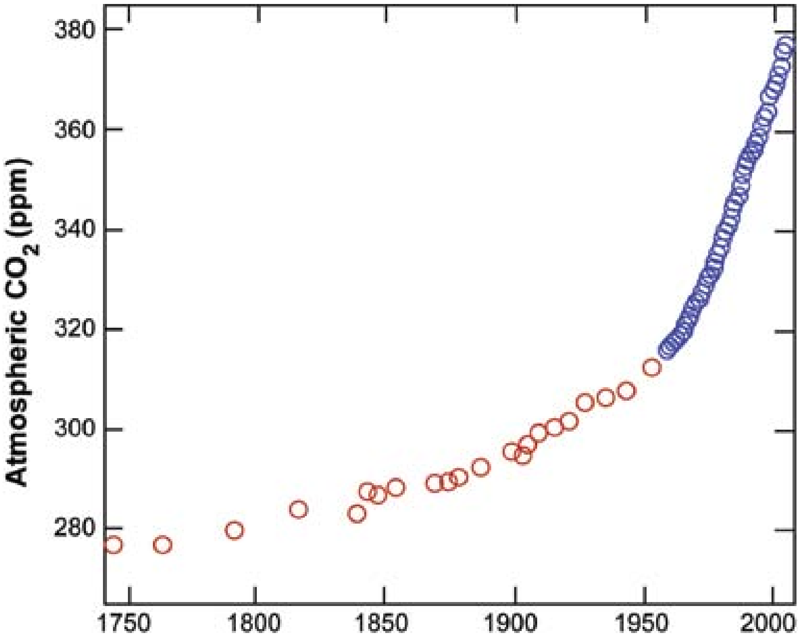


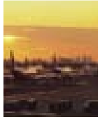
Figure 2.2 Atmospheric CO_2 concentration from 1750 to 2005. The data prior to 1957 (red circles) are from the Siple ice core (Friedli et al., 1986). The data since 1957 (blue circles) are from continuous atmospheric sampling at the Mauna Loa Observatory (Hawaii) (Keeling *et al.*, 1976; Thoning *et al.*, 1989) (with updates available at http://cdiac.ornl.gov/trends/co2/sio-mlo.htm).

The recent subsidy, or sequestration, of carbon by the unmanaged parts of the carbon cycle, makes them critical for an accurate understanding of climate change. Future increases in carbon uptake in the unmanaged parts of the cycle could moderate the risks from climate change, while decreases or transitions from uptake to release could amplify the risks, perhaps dramatically.

In addition to its role in the climate, the carbon cycle intersects with a number of critical Earth system processes. Because plant growth is essentially the removal of CO_2 from the air through photosynthesis, agriculture and forestry contribute important fluxes. Wildfire is a major release of carbon from plants and soils to the atmosphere (Sabine *et al.*, 2004b). The increasing concentration of CO_2 in the atmosphere has already made the world's oceans more acid (Caldeira and Wickett, 2003). Future changes could dramatically alter the composition of ocean ecosystems (Feely *et al.*, 2004; Orr *et al.*, 2005).

2.1.1 The Unmanaged Global Carbon Cycle

The modern background, or unmanaged, carbon cycle includes the processes that occur in the absence of human actions. However, these processes are currently so altered by human influences on the carbon cycle that it is not appropriate to label them natural. This background part of the carbon cycle is dominated by two pairs of gigantic fluxes with annual uptake and release that are close to balanced (Sabine *et al.*, 2004b) (Figure 2.1). The first of these comprises the terrestrial carbon cycle: plant growth on land annually fixes about 57 ± 9 Gt of atmospheric carbon, approximately ten times the annual emission from fossil-fuel combustion, into carbohydrates. Respiration by land plants, animals, and microorganisms, which provides the energy for growth, activity, and reproduction, returns a slightly smaller amount to the atmosphere. Part of the difference between photosynthesis and respiration is burned in wildfires, and part is stored as plant material or soil organic carbon. The second comprises the ocean carbon cycle: about 92 Gt of atmospheric carbon dissolves annually in the oceans, and about 90 Gt per year moves from the oceans to the atmosphere (While the gross fluxes have a substantial uncertainty, the difference is known to within ± 0.2 Gt)[3]. These air-sea fluxes are driven by cycling within the oceans that governs exchanges between pools of dissolved CO_2, bicarbonate (HCO_3), carbonate (CO_3), organic matter, and calcium carbonate ($CaCO_3$).



Before the beginning of the industrial revolution, carbon uptake and release through these two pairs of large fluxes were almost balanced, with carbon uptake on land of approximately 0.45 ± 0.18 Gt C per year transferred to the oceans by rivers and released from the oceans to the atmosphere (Jacobson *et al.*, 2007). As a consequence, the level of CO_2 in the atmosphere varied by less than 25 parts per million (ppm) in the 10,000 years prior to 1850 (Joos and Prentice, 2004). However, atmospheric CO_2 was not always so stable. During the preceding 420,000 years, atmospheric CO_2 was 180-200 ppm during the ice ages and approximately 275 ppm during interglacial periods (Petit *et al.*, 1999). The lower ice-age concentrations in the atmosphere most likely reflect a transfer of carbon from the atmosphere to the oceans, possibly driven by changes in ocean circulation and sea-ice cover (Sigman and Boyle, 2000; Keeling and Stephens, 2001). Enhanced biological activity in the oceans, stimulated by increased delivery of iron-rich terrestrial dust, may have also contributed to this increased uptake (Martin, 1990).

The increasing concentration of CO_2 in the atmosphere has already made the world's oceans more acid. Future changes could dramatically alter the composition of ocean ecosystems.

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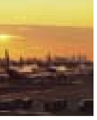
[3] This uncertainty is one-half the range among the subset of the 19 Ocean Carbon-Cycle Model Intercomparison Project (OCMIP) models that are consistent with the available ^{14}C and CFC-11 data (Matsumoto *et al.*, 2004).

Per capita emissions in the United States were nearly 5 times the world average, 2.5 times the *per capita* emissions for Western Europe, and more than 8 times the average for Asia and Oceania.



In the distant past, the global carbon cycle was out of balance in a different way. Fossil fuels are the product of prehistorically stored plant growth, especially 354 to 290 million years ago in the Carboniferous period. During this time, luxuriant plant growth and geological activity combined to bury a small fraction of each year's growth. Over millions of years, this gradual burial led to the accumulation of vast stocks of fossil fuel. The total accumulation of fossil fuels is uncertain, but probably in the range of 6000 ± 3000 Gt (Sabine *et al.*, 2004b). This burial of carbon also led to a near doubling of atmospheric oxygen (Falkowski *et al.*, 2005).

2.1.2 Human-induced Perturbations to the Carbon Cycle

Since the beginning of the industrial revolution, there has been a massive release of carbon from fossil-fuel combustion and deforestation. Cumulative carbon emissions from fossil-fuel combustion, natural gas flaring, and cement manufacturing from 1751 through 2003 are 304 ± 30 Gt (Marland and Rotty, 1984; Andres *et al.*, 1999)[4]. Land-use change from 1850 to 2003, mostly from forest clearing, added another 162±160 Gt (DeFries *et al.*, 1999; Houghton, 1999)[5]. The rate of fossil-fuel consumption in any recent year would have required, for its production, more than 400 times the current global primary production (total plant growth) of the land and oceans combined (Dukes, 2003). This has led to a rapid increase in the concentration of CO_2 in the atmosphere since the mid-1800s, with atmospheric CO_2 rising by 31% (*i.e.*, from 287 ppm to 375 ppm in 2003; the increase from the mid-1700s was 35%).

In 2004, the three major countries of North America (Canada, Mexico, and the United States) together accounted for carbon emissions from fossil-fuel combustion of approximately 1.88 ± 0.2 Gt C, (about 25%) of the global total[6]. The United States, the world's largest emitter of CO_2, was responsible for 86% of the North American total. *Per capita* emissions in 2004 were 5.5 ± 0.5 metric tons in the United States, 4.9 ± 0.5 metric tons in Canada, and 1.0 ± 0.1 metric tons in Mexico. *Per capita* emissions in the United States were nearly 5 times the world average, 2.5 times the *per capita* emissions for Western Europe, and more than 8 times the average for Asia and Oceania (DOE EIA, 2006). The world's largest countries, China and India, have total carbon emissions from fossil-fuel combustion and the flaring of natural gas that are growing rapidly. The 2004 total for China was 80% of that in the United States, and the total for India was 18% of that in the United States. *Per capita* emissions for China and India in 2004 were 18% and 5%, respectively, of the United States rate (DOE EIA, 2006).

2.2 ASSESSING GLOBAL AND REGIONAL CARBON BUDGETS

Changes in the carbon content of the oceans and plants and soils on land can be evaluated with at least five different approaches—flux measurements, inventories, inverse estimates based on atmospheric CO_2, process models, and calculation as a residual. The first method, direct measurement of carbon flux, is well developed over land for measurements over the spatial scale of up to 1 km^2, using the eddy flux technique (Wofsy *et al.*, 1993; Baldocchi and Valentini, 2004). Although eddy flux measurements are now collected at more than 100 networked sites, spatial scaling presents formidable challenges due to spatial heterogeneity. To date, estimates of continental-scale fluxes based on eddy flux must be regarded as preliminary. Over the oceans, eddy flux is possible (McGillis, 2001), but estimates based on air-sea CO_2 concentration difference are more widely used (Takahashi *et al.*, 1997).

Inventories, based on measuring trees on land (Birdsey and Heath, 1995) or carbon in ocean-water samples (Takahashi *et al.*, 2002; Sabine *et al.*, 2004a) can provide useful constraints on changes in the size of carbon pools, though their utility for quantifying short-term changes is limited. Inventories were the foundation of the recent conclusion that 118 ± 19 Gt of human-caused carbon entered the oceans through 1994 (Sabine *et al.*, 2004a) and that forests in the mid latitudes of the Northern Hemisphere absorbed and stored 0.6 to 0.7 Gt C per year in the 1990s (Goodale *et al.*, 2002). Changes in the atmospheric inventory of oxygen (O_2) (Keeling *et al.*, 1996) and carbon-13 (^{13}C) in CO_2 (Siegenthaler and Oeschger, 1987) provide a basis for partitioning CO_2 flux into land and ocean components.

Process models and inverse estimates based on atmospheric CO_2 (or CO_2 in combination with ^{13}C or O_2) also provide use-

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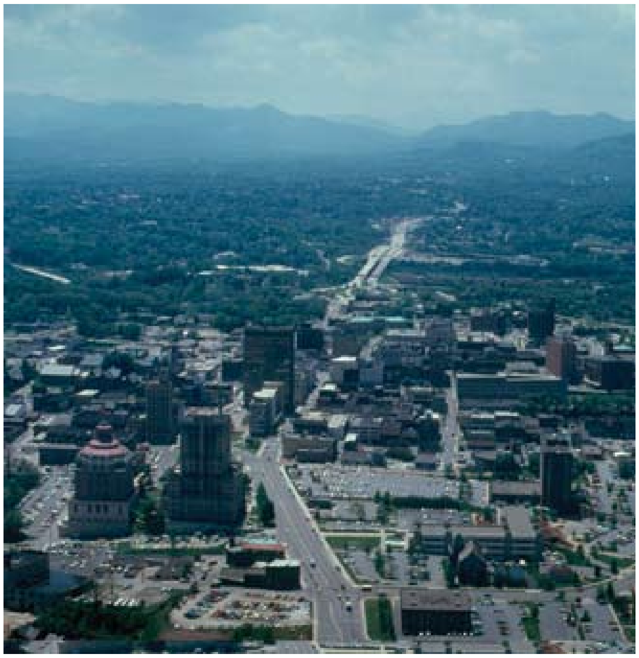
[4] Updates through 2003 available at http://cdiac.ornl.gov/trends/mis/tre_glob.html.

[5] Updates through 2000 online at http://cdiac.ornl.gov/trends/landuse/houghton/houghton.html. The total through 2003 was extrapolated based on the assumption that the annual fluxes in 2001-2003 were the same as in 2000.

[6] Uncertainties in national and *per capita* emissions are based on data reported by individual countries.

ful constraints on carbon stocks and fluxes. Process models build from understanding the underlying principles of atmosphere/ocean or atmosphere/ecosystem carbon exchange to make estimates over scales of space and time that are relevant to the global carbon cycle. For the oceans, calibration against observations with tracers (*e.g.*, carbon-14 [^{14}C] and chlorofluorocarbons) (Broecker *et al.*, 1980) tends to nudge a wide range of models toward similar results. Sophisticated models with detailed treatment of the ocean circulation, chemistry, and biology all reach about the same estimate for the current ocean carbon sink, 1.5 to 1.8 Gt C per year (Greenblatt and Sarmiento, 2004) and are in quantitative agreement with data-inventory approaches. Models of the land carbon cycle take a variety of approaches. They differ substantially in the data used as constraints, in the processes simulated, and in the level of detail (Cramer *et al.*, 1999; Cramer *et al.*, 2001). Models that take advantage of satellite data have the potential for comprehensive coverage at high spatial resolution (Running *et al.*, 2004), but only over the time domain with available satellite data. Flux components related to human activities, deforestation, for example, have been modeled based on historical land use (Houghton *et al.*, 1999). At present, model estimates are uncertain enough that they are often used most effectively in concert with other kinds of estimates (*e.g.*, Peylin *et al.*, 2005).

Inverse estimates based on atmospheric gases (CO_2, ^{13}C in CO_2, or O_2) infer surface fluxes based on the spatial and temporal pattern of atmospheric gas concentration, coupled with information on atmospheric transport (Newsam and Enting, 1988). The atmospheric concentration of CO_2 is now measured with high precision at approximately 100 sites worldwide, with many of the stations added in the last decade (Masarie and Tans, 1995). The ^{13}C in CO_2 and high-precision O_2 are measured at far fewer sites. The basic approach is a linear Bayesian inversion (Tarantola, 1987; Enting, 2002), with many variations in the time scale of the analysis, the number of regions used, and the transport model. Inversions have more power to resolve year-to-year differences than mean fluxes (Rodenbeck *et al.*, 2003; Baker *et al.*, 2006). Limitations in the accuracy of atmospheric inversions come from the limited density of concentration measurements (especially in the tropics), uncertainty in the transport, and errors in the inversion process (Baker *et al.*, 2006). Recent studies that use a number of sets of CO_2 monitoring stations (Rodenbeck *et al.*, 2003), models (Gurney *et al.*, 2003; Law *et al.*, 2003; Gurney *et al.*, 2004; Baker *et al.*, 2006), temporal scales, and spatial regions (Pacala *et al.*, 2001), highlight the sources of the uncertainties and appropriate steps for managing them.

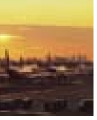


A final approach to assessing large-scale CO_2 fluxes is solving as a residual. At the global scale, the net flux to or from the land is often calculated as the residual left after accounting for fossil-fuel emissions, atmospheric increase, and ocean uptake (Post *et al.*, 1990). Increasingly, the need to treat the land as a residual is receding, as the other methods improve. Still, the existence of constraints at the level of the overall budget provides an important connection with reality.

2.3 RECENT DYNAMICS OF THE UNMANAGED CARBON CYCLE

Of the approximately 466 ± 160 Gt C added to the atmosphere by human actions through 2003, only about 187 ± 5 Gt remain. The "missing carbon" must be stored, at least temporarily, in the oceans and in ecosystems on land. Based on a recent ocean inventory, 118 ± 19 Gt of the missing carbon was in the oceans, as of 1994 (Sabine *et al.*, 2004a). Extending this calculation, based on recent sinks (Takahashi *et al.*, 2002; Gloor *et al.*, 2003; Gurney *et al.*, 2003; Matear and McNeil, 2003; Matsumoto *et al.*, 2004), leads to an estimate of 137 ± 24 Gt C through 2003. This leaves about 142 ± 160 Gt that must be stored on land (with most of the uncertainty due to the uncertainty in emissions from land use). Identifying the processes responsible for the uptake on land, their spatial distribution, and their likely future trajectory has been one of the major goals of carbon cycle science over the last decade.

Much of the recent research on the global carbon cycle has focused on annual fluxes and their spatial and temporal variation. The temporal and spatial patterns of carbon flux provide a pathway to understanding the underlying mechanisms. Based on several different approaches, carbon



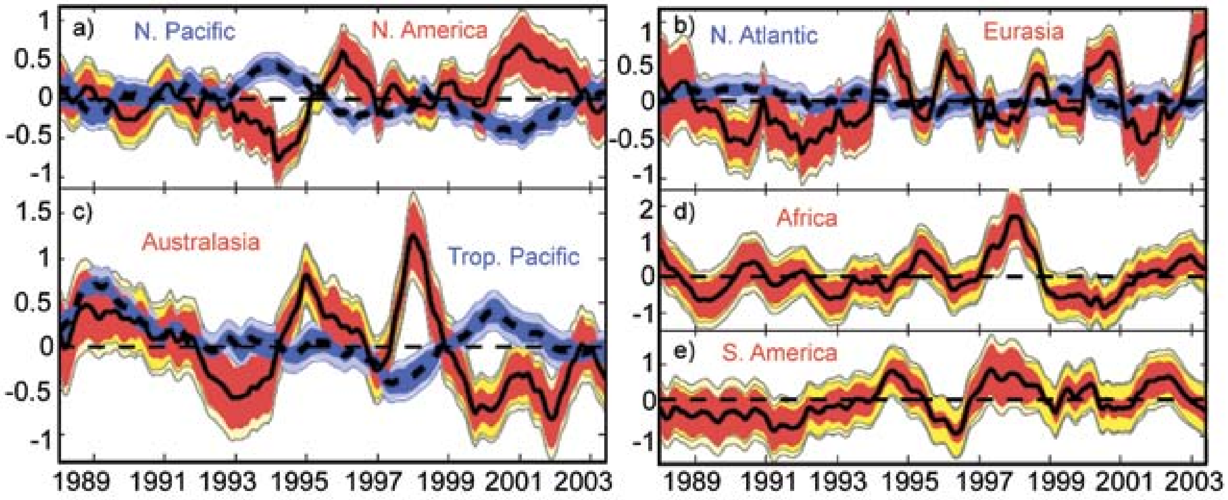


Figure 2.3 The 13-model mean CO_2 flux interannual variability (Gt C per year) for several continents (solid lines) and ocean basins (dashed lines). In each panel, the dark inner band is the 1σ intermodel spread, the lighter adjacent band is the 1σ estimation uncertainty on interannual variability, and the outer band (visible only for the land) is the root sum of squares of the two uncertainty components. (a) North Pacific and North America, (b) Atlantic north of 15°N and Eurasia, (c) Australasia and Tropical Pacific, (d) Africa, and (e) South America (note the different scales for Africa and South America) (Baker *et al.*, 2006).

uptake by the oceans averaged 1.7 ± 0.2 Gt C per year[7] for the period from 1992-1996 (Takahashi *et al.*, 2002; Gloor *et al.*, 2003; Gurney *et al.*, 2003; Matear and McNeil, 2003; Matsumoto *et al.*, 2004). The total human-caused flux is this amount, plus 0.45 Gt per year of preindustrial outgasing, for a total of 2.2 ± 0.4 Gt per year. This rate represents an integral over high-latitude areas, which are gaining carbon, and the tropics, which are losing carbon (Takahashi *et al.*, 2002; Gurney *et al.*, 2003; Gurney *et al.*, 2004; Jacobson *et al.*, 2007). Interannual variability in the ocean sink for CO_2, though substantial (Greenblatt and Sarmiento, 2004), is much smaller than interannual variability on the land (Baker *et al.*, 2006).

In the 1990s, carbon releases from land-use change were more than balanced by ecosystem uptake, leading to a net sink on land (without accounting for fossil-fuel emissions) of 1.1 ± 1.5 Gt C per year (Schimel *et al.*, 2001; Sabine *et al.*, 2004b). The dominant sources of recent interannual variation in the net land flux were El Niño and the eruption of Mount Pinatubo in 1991 (Bousquet *et al.*, 2000; Rodenbeck *et al.*, 2003; Baker *et al.*, 2006), with most of the year-to-year variation in the tropics (Figure 2.3). Fire likely plays a large role in this variability (van der Werf *et al.*, 2004).

In the 1990s, carbon releases from land-use change were more than balanced by ecosystem uptake, leading to a net sink on land (without accounting for fossil-fuel emissions).

On a time scale of thousands of years, the ocean will be the sink for more than 90% of the carbon released to the atmosphere by human activities (Archer *et al.*, 1998). The rate of CO_2 uptake by the oceans is, however, limited. Carbon dioxide enters the oceans by dissolving in seawater. The rate of this process is determined by the concentration difference between the atmosphere and the surface waters and by an air-sea exchange coefficient related to wave action, wind, and turbulence (Le Quéré and Metzl, 2004). Because the surface waters represent a small volume with limited capacity to store CO_2, the major control on ocean uptake is at the level of moving carbon from the surface to intermediate and deep waters. Important contributions to this transport come from the large-scale circulation of the oceans, especially the sinking of cold water in the Southern Ocean and, to a lesser extent, the North Atlantic.

On land, numerous processes contribute to carbon storage and carbon loss. Some of these are directly influenced through human actions (*e.g.*, the planting of forests, conversion to no-till agriculture, or the burying of organic wastes in landfills). The human imprint on others is indirect. This category includes ecosystem responses to climate change (*e.g.*, warming and changes in precipitation), changes in the composition of the atmosphere (*e.g.*, increased CO_2 and increased tropospheric ozone), and delayed consequences of past actions (*e.g.*, regrowth of forests after earlier harvesting). Early analyses of the global carbon budget (*e.g.*, Bacastow and Keeling, 1973) typically assigned all of the net flux on land to a single mechanism, fertilization of plant growth by increased atmospheric CO_2. Recent evidence emphasizes the diversity of mechanisms.

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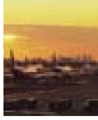
[7] This uncertainty is one-half the range among the subset of the 19 Ocean Carbon-Cycle Model Intercomparison Project (OCMIP) models that are consistent with the available ^{14}C and CFC-11 data (Matsumoto *et al.*, 2004).

2.3.1 The Carbon Cycle of North America

The land area of North America is a large source of carbon, but the residual (without emissions from fossil-fuel combustion) is, by most estimates, currently a sink for carbon. This conclusion for the continental scale is based mainly on the results of atmospheric inversions. Several studies address the carbon balance of particular ecosystem types (*e.g.*, forests [Kurz and Apps, 1999; Goodale *et al.*, 2002; Chen *et al.*, 2003]). Pacala and colleagues (2001) used a combination of atmospheric and land-based techniques to estimate that the 48 contiguous United States are currently a carbon sink of 0.3 to 0.6 Gt C per year. This estimate and a discussion of the processes responsible for recent sinks in North America are updated in Chapter 3 of this report. Based on inversions using 13 atmospheric transport models, North America was a carbon sink of 0.97 ± 0.36 Gt C per year from 1991-2000 (Baker *et al.*, 2006)[8]. Over the area of North America, this amounts to an annual carbon sink of 39.6 g C per square meter per year, similar to the sink inferred for all northern lands (North America, Europe, Boreal Asia, and Temperate Asia) of 32.5 g C per square meter per year (Baker *et al.*, 2006).

Very little of the current carbon sink in North America is a consequence of deliberate action to absorb and store (sequester) carbon. Some is a collateral benefit of steps to improve land management, for increasing soil fertility, improving wildlife habitat, *etc*. Much of the current sink is unintentional, a consequence of historical changes in technologies and preferences in agriculture, transportation, and urban design.

The land area of North America is a large source of carbon, but the residual (without emissions from fossil-fuel combustion) is, by most estimates, currently a sink for carbon.



2.4 CARBON CYCLE OF THE FUTURE

The future trajectory of carbon sinks in North America is very uncertain. Several trends will play a role in determining the sign and magnitude of future changes. One important controller is the magnitude of future climate changes. If the climate warms significantly, much of the United States could experience drought-related decreases in plant growth and an increase in the risk of wildfire (Bachelet *et al.*, 2003), especially if the warming is not associated with substantial increases in precipitation. Exactly this pattern—substantial warming with little or no change in precipitation—characterizes North America in many of the newer climate simulations (Rousteenoja *et al.*, 2003). If North American ecosystems are sensitive to elevated CO_2, nitrogen deposition, or warming, plant growth could increase (Schimel *et al.*, 2000). The empirical literature on CO_2 and nitrogen deposition is mixed, with some reports of substantial growth enhancement (Norby *et al.*, 2005) and others reporting small or modest effects (Oren *et al.*, 2001; Shaw *et al.*, 2002; Heath *et al.*, 2005).

Overall, the carbon budget of North America is dominated by carbon releases from the combustion of fossil fuels. Recent sinks, largely from carbon uptake in plants and soils, may approach 50% of the recent fossil-fuel source (Baker *et al.*, 2006). Most of this uptake appears to be a rebound, as natural and managed ecosystems recover from past disturbances. Little evidence supports the idea that these ecosystem sinks will increase in the future. Substantial climate change could convert current sinks into sources (Gruber *et al.*, 2004).

In the future, trends in the North American energy economy may intersect with trends in the natural carbon cycle. A large-scale investment in afforestation could offset substantial future emissions (Graham, 2003). However, costs of this kind of effort would include loss of the new-forested area from its previous uses (including grazing or agriculture), the energy costs of managing the new

Very little of the current carbon sink in North America is a consequence of deliberate action to absorb and store (sequester) carbon.

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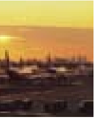
[8] This uncertainty is a sample standard deviation across monthly output from 13 models.



forests, and any increases in emissions of non-CO_2 greenhouse gases from the new forests. Large-scale investments in biomass energy (energy produced from vegetative matter) would have similar costs but would result in offsetting emissions from fossil-fuel combustion, rather than sequestration (Giampietro *et al.*, 1997). The relative costs and benefits of investments in afforestation and biomass energy will require careful analysis (Kirschbaum, 2003). Investments in other energy technologies, including wind and solar, will require some land area, but the impacts on the natural carbon cycle are unlikely to be significant or widespread (Hoffert *et al.*, 2002; Pacala and Socolow, 2004).

Like the present, the carbon cycle of North America during the next several decades will be dominated by fossil-fuel emissions. Deliberate geological sequestration may become an increasingly important component of the budget sheet. Still, progress in controlling the net release to the atmosphere must be centered on the production and consumption of energy rather than the processes of the unmanaged carbon cycle. North America has many opportunities to decrease emissions (Chapter 4 this report). Nothing about the status of the unmanaged carbon cycle provides a justification for assuming that it can compensate for emissions from fossil-fuel combustion.

Nothing about the status of the unmanaged carbon cycle provides a justification for assuming that it can compensate for emissions from fossil-fuel combustion.

CHAPTER 3

The North American Carbon Budget Past and Present

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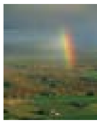
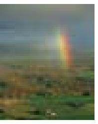


KEY FINDINGS

- Fossil-fuel carbon emissions in the United States, Canada, and Mexico totaled 1856 million tons per year in 2003 (plus or minus 10%). This represents 27% of global fossil-fuel emissions.
- Approximately 30% of North American fossil-fuel emissions are offset by a natural sink estimated at 505 million tons of carbon per year (plus or minus 50%) for the period including 2003 caused by a variety of factors, including forest regrowth, wildfire suppression, and agricultural soil conservation.
- In 2003, North America emitted a net of 1351 million tons of carbon per year (plus or minus 25%) to the atmosphere.
- North American carbon dioxide emissions from fossil fuel have increased at an average rate of approximately 1% per year for the last 30 years.
- Growth in emissions accompanies the historical growth in the industrial economy and Gross Domestic Product (GDP) of North America. However, at least in the United States and Canada, the rate of emissions growth is less than the growth in GDP, reflecting a decrease in the carbon intensity of these economies.
- Fossil-fuel emissions from North America are expected to continue to grow, but more slowly than GDP.
- Historically, the plants and soils of the United States and Canada were sources for atmospheric carbon dioxide, primarily as a consequence of the expansion of croplands into forests and grasslands. In recent decades these regions have shifted from source to sink as forests recover from agricultural abandonment, fire suppression is practiced, and logging is reduced, and as a result, these regions are now accumulating carbon. In Mexico, emissions of carbon continue to increase due to net deforestation.
- The future of the North American carbon sink is highly uncertain. The contribution of recovering forests to this sink is likely to decline as these forests mature, but we do not know how much of the sink is due to fertilization of the ecosystems by nitrogen in air pollution and by increasing carbon dioxide concentrations in the atmosphere, nor do we understand the impact of ozone in the lower atmosphere or how the sink will change as the climate changes. Increases in decomposition and wildfire caused by climate change could, in principle, convert the sink into a source.
- The current magnitude of the North American sink offers the possibility that significant mitigation of fossil-fuel emissions could be accomplished by managing forests, rangelands, and croplands to increase the carbon stored in them. However, the range of uncertainty in these estimates is at least as large as the estimated values themselves.
- Current trends towards lower carbon intensity of United States' and Canadian economies increase the likelihood that a portfolio of carbon management technologies will be able to reduce the 1% annual growth in fossil-fuel emissions. This same portfolio might be insufficient if carbon emissions were to begin rising at the approximately 3% growth rate of GDP.

3.1 FOSSIL FUEL

Fossil-fuel carbon emissions in the United States, Canada, and Mexico totaled 1856 million metric tons of carbon (Mt C) per year in 2003 and have increased at an average rate of approximately 1% per year for the last 30 years (United States = 1582, Canada = 164, Mexico = 110 Mt C per year, see Figure 3.1)[1]. This represents 27% of global emissions, from a continent with 7% of the global population and 25% of global GDP (EIA, 2005).



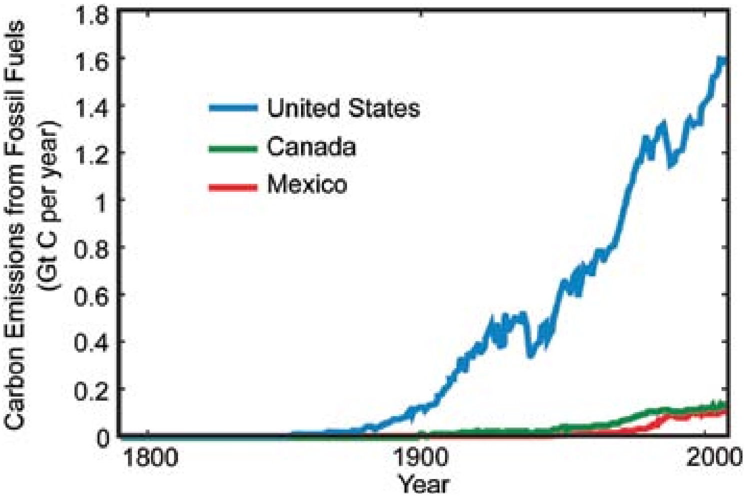


Figure 3.1 Historical carbon emissions from fossil fuel in the United States, Canada, and Mexico. Data from the U.S. Energy Information Administration (EIA, 2005).

The United States is the world's largest emitter in absolute terms (EIA, 2005). The United States' *per capita* emissions are also among the largest in the world (5.4 t C per year), but the carbon intensity of its economy (emissions per unit GDP) at 0.15 metric tons of emitted carbon per dollar of GDP is close to the world's average of 0.14 t C/$ (EIA, 2005). Total United States' emissions have grown at close to the North American average rate of about 1.0% per year over the past 30 years, but the United States' *per capita* emissions have been roughly constant, while the carbon intensity of the United States' economy has decreased at a rate of about 2% per year (see Figures 3.1 to 3.4).

Absolute emissions grew at 1% per year even though *per capita* emissions were roughly constant simply because of population growth at an average rate of 1%. The constancy of United States' *per capita* values masks faster than 1% growth in some sectors (*e.g.*, transportation) that was balanced by slower growth in others (*e.g.*, increased manufacturing energy efficiency) (Figures 3.2, 3.3, and 3.4).

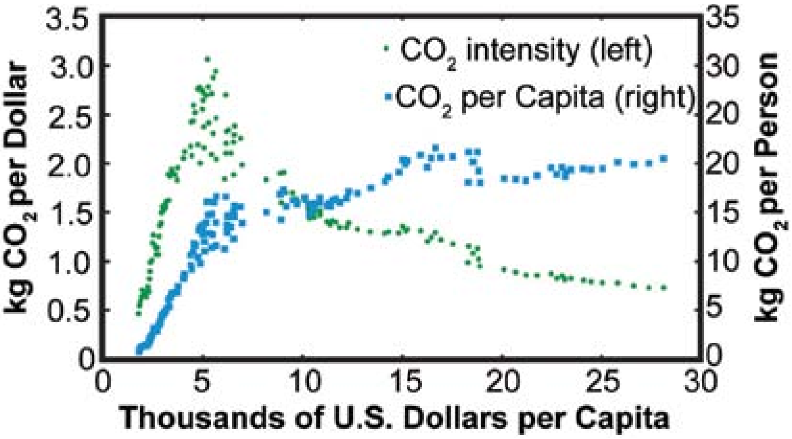


Figure 3.2 The historical relationship between United States' *per capita* GDP and United States' carbon intensity (green symbols, kg CO_2 emitted per 1995 dollar of GDP) and *per capita* carbon emissions (blue symbols, kg CO_2 per person). Each symbol shows a different year and each of the two time series progresses roughly chronologically from left (early) to right (late) and ends in 2002. *Source:* Maddison (2003), Marland *et al.* (2005). Thus, the blue square farthest to the right shows United States' *per capita* CO_2 emissions in 2002. The square second farthest to the right shows *per capita* emissions in 2001. The third farthest to the right shows 2000, and so on. Note that *per capita* emissions have been roughly constant over the last 30 years (squares corresponding to *per capita* GDP greater than approximately $16,000).

Historical decreases in United States' carbon intensity began early in the twentieth century and continue despite the approximate stabilization of *per capita* emissions (Figure 3.2). Why has the United States' carbon intensity declined? This question is the subject of extensive literature on the so-called structural decomposition of the energy system and on the relationship between GDP and the environment (*i.e.*, Environmental Kuznets Curves; Grossman and Krueger, 1995; Selden and Song, 1994). See, for example, Greening *et al.* (1997, 1998), Casler and Rose (1998), Golove and Schipper (1998), Rothman (1998), Suri and Chapman (1998), Greening *et al.* (1999), Ang and Zhang (2000), Greening *et al.* (2001), Davis *et al.* (2002), Kahn (2003), Greening (2004), Lindmark (2004), Aldy (2005), and Lenzen *et al.* (2006).

Possible causes of the decline in United States' carbon intensity include: structural changes in the economy, technological improvements in energy efficiency, behavioral changes by consumers and producers, the growth of renewable and nuclear energy, and the displacement of oil consumption

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[1] Uncertainty estimates for the numerical data presented in this chapter can be found in Tables 3.1 through 3.3.

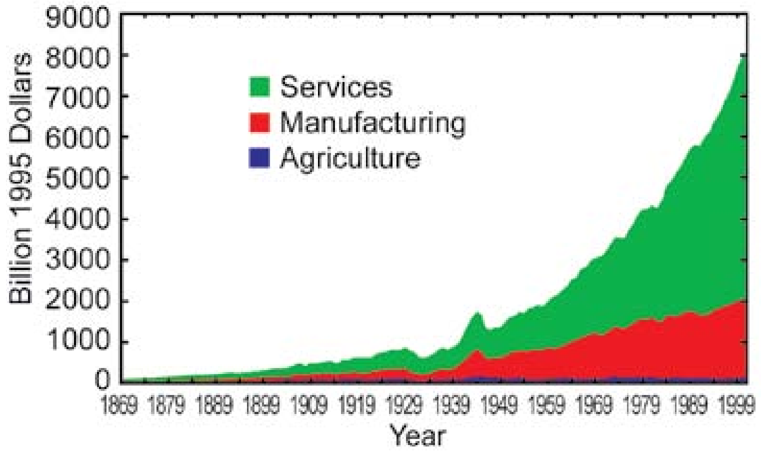
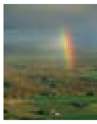


Figure 3.3 Historical United States' GDP divided among the manufacturing, services, and agricultural sectors. *Source:* Mitchell (1998), WRI (2005).

by gas and/or of coal consumption by oil and gas (if we produce the same amount of energy from coal, oil, and gas, then the emissions from oil are only 80% of those from coal, and from gas only 75% of those from oil) (Casler and Rose, 1998; Ang and Zhang, 2000). The last two items on this list are not dominant causes because we observe that both primary energy consumption and carbon emissions grew at close to 1% per year over the past 30 years (EIA, 2005). At least in the United States, there has been no significant decarbonization of the energy system during this period. However, all of the other items on the list play a significant role. The economy has grown at an annual rate of 2.8% over the last three decades because of 3.6% growth in the service sector; manufacturing grew at only 1.5% per year (Figure 3.3). Because the service sector has much lower carbon intensity than manufacturing, this faster growth of services reduces the country's carbon intensity. If all of the growth in the service sector had been in manufacturing from 1971 to 2001, then the emissions would have grown at 2% per year instead of 1% (here we equate the manufacturing sector in Figure 3.3 with the industrial sector in Figure 3.4). So, structural change is at least one-half of the answer. Because the service sector is likely to continue to grow more rapidly than other sectors of the economy, we expect that carbon emissions will continue to grow more slowly than GDP. This is important because it implies considerable elasticity in the relationship between emissions growth and economic growth. It also widens the range of policy options that are now technologically possible. For example, a portfolio of current technologies able to convert the 1% annual growth in emissions into a 1% annual decline, might be insufficient if carbon emissions were to begin rising at the ~3% growth rate of GDP (Pacala and Socolow, 2004).

However, note that industrial emissions are approximately constant (Figure 3.4) despite 1.5% economic growth in manufacturing (Figure 3.3). This decrease in carbon intensity is caused both by within-sector structural shifts (*i.e.*, from heavy to light manufacturing) and by technological improvements (See Part II of this report). Emissions from the residential sector are growing at roughly the same rate as the population (Figure 3.4; 30-year average of 1.0% per year), while emissions from transportation are growing faster than the population, but slower than GDP (Figure 3.4; 30-year average of 1.4% per year). The difference between the 3% growth rate of GDP and the 1.6% growth in emissions from transportation is not primarily due to technological improvement because carbon emissions per mile traveled have been level or increasing over the period (Chapter 7 this report).

> We expect that carbon emissions will continue to grow more slowly than GDP. This is important because it widens the range of policy options that are now technologically possible.



3.2 CARBON SINKS[2]

Approximately 30% of North American fossil-fuel emissions are offset by a natural sink estimated at 505 Mt C per year caused by a variety of factors, including forest regrowth, fire suppression, and agricultural soil conservation. The sink absorbs 489 Mt C per year in the United States and 64 Mt C per year in Canada. Mexican ecosystems create a net source of 48 Mt C per year. Rivers and international trade also export a net of 161 Mt C per year that was captured from the atmosphere by the continent's ecosystems, and so North America absorbs 666 Mt C per year of atmospheric CO_2 (666 = 505 + 161). Because most of these net exports will return

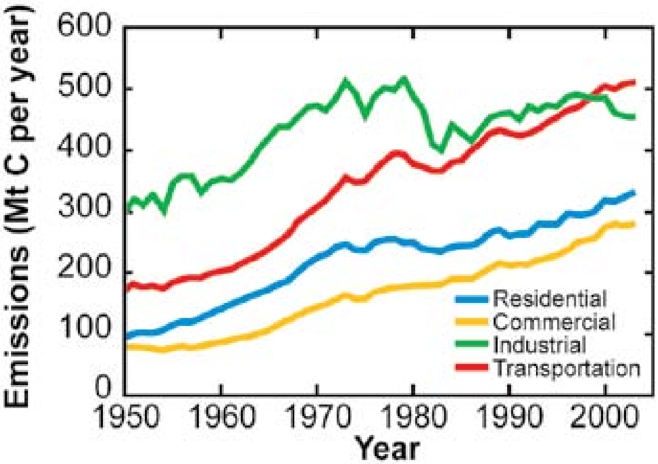


Figure 3.4 Historical United States' carbon emissions divided among the residential, services, manufacturing, and transportation sectors. *Source:* EIA (2005).

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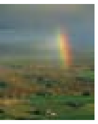
[2] See Tables 3.1 and 3.2 for estimates, citations, and uncertainty of estimates

to the atmosphere elsewhere within 1 year (*e.g.* carbon in exported grain will be eaten, metabolized, and exhaled as CO_2), the net North American sink is rightly thought of as 505 Mt C per year even though the continent absorbs a net of 666 Mt C per year. Moreover, coastal waters may be small net emitters to the atmosphere at the continental scale (19 Mt C per year), but this flux is highly uncertain (Chapter 15 this report). The portion of the coastal flux caused by human activity is thought to be close to zero, so coastal sea-air exchanges should be excluded from the continental carbon sink.



As reported in Chapter 2, the sink in the United States is approximately 40% (plus or minus 20%) the size of the global carbon sink, while the sink in Canada is about 7% (plus or minus 7%) the size of the global sink. The source in Mexico reduces the global sink by ~4% (plus or minus more than 4%). The reason for the disproportionate importance of United States' sinks is probably the unique land-use history of the country (summary in Appendix A). During European settlement, large amounts of carbon were released from the harvest of virgin forests and the plowing of virgin soils to create agricultural lands. The abandonment of many of the formerly agricultural lands in the east and the regrowth of forest is a unique event globally and is responsible for about one-half of the United States' sink (Houghton *et al.*, 2000). Most of the United States' sink thus represents a one-time recapture of some of the carbon that was released to the atmosphere during settlement. In contrast, Mexican ecosystems, like those of many tropical nations, are still a net carbon source because of ongoing deforestation (Masera *et al.*, 1997).

The non-fossil fluxes in Tables 3.1 and 3.2 are derived exclusively from inventory methods in which the total amount of carbon in a pool (*i.e.*, living forest trees plus forest soils) is measured on two occasions. The difference between the two measurements shows if the pool is gaining (sink) or losing (source) carbon. Carbon inventories are straightforward in principle, but of uneven quality in practice. For example, we know the carbon in living trees in the United States relatively accurately because the U.S. Forest Service Forest Inventory program measures trees systematically in more than 200,000 locations. However, we must extrapolate from a few measurements of forest soils with models because there is no national inventory of carbon in forest soils.

Although the fluxes in Tables 3.1 and 3.2 represent the most recent published estimates, with most less than five years old, a few are older than ten years (see the citations at the bottom of each table). Also, the time interval between inventories varies among the elements of the tables, with most covering a five to ten year period. In these tables and throughout this document we report uncertainties using the six categories outlined in Box 3.1.

Table 3.1 Annual net emissions (source = positive) or uptake (land sink = negative) of carbon in millions of tons circa 2003 (see Box 3.1 for uncertainty conventions).

Source (positive) or Sink (negative)	United States	Canada	Mexico	N. America
Fossil source (positive)				
Fossil fuel (oil, gas, coal)	1582[a,*****] (681, 328, 573)	164[a,*****] (75, 48, 40)	110[a,*****] (71, 29, 11)	1856***** (828, 405, 624)
Non-fossil carbon sink (negative) or source (positive)				
Forest	–256[b,***]	–28[c,***]	+52[d,**]	–233***
Wood products	–57[e,***]	–11[f,***]	ND	–68***
Woody encroachment	–120[g,*]	ND	ND	–120*
Agricultural soils	–8[h,***]	–2[h,***]	ND	–10[h,***]
Wetlands	–23[i,*]	–23[i,*]	–4[i,*]	–49*
Rivers and reservoirs	–25[j,**]	ND	ND	–25*
Total carbon source or sink	–489***	–64**	48*	–505***
Net carbon source (positive)	1093****	100***	158***	1351****

[a] http://www.eia.doe.gov/env/inlenv.htm

[b] Smith and Heath (2005) for above-ground carbon, but including 20 Mt C per year for United States' urban and suburban forests from Chapter 14, and Pacala *et al.* (2001) for below-ground carbon.

[c] Environment Canada (2006), Chapter 11, plus 11 Mt C per year for Canadian urban and suburban forests, Chapter 14.

[d] Masera et *al.* (1997)

[e] Skog *et al.* (2004), Skog and Nicholson (1998)

[f] Goodale et *al.* (2002)

[g] Houghton *et al.* (1999), Hurtt *et al.* (2002), Houghton and Hackler (1999).

[h] Chapter 10; Uncertain; Could range from -7 Mt C per year to -14 Mt C per year for North America.

[i] Chapter 13

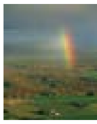
[j] Stallard (1998); Pacala *et al.* (2001)

ND indicates that no data are available.

BOX 3.1: CCSP SAP 2.2 Uncertainty Conventions

***** = 95% certain that the actual value is within 10% of the estimate reported,
**** = 95% certain that the estimate is within 25%,
*** = 95% certain that the estimate is within 50%,
** = 95% certain that the estimate is within 100%, and
* = uncertainty greater than 100%.
† = The magnitude and/or range of uncertainty for the given numerical value(s) is not provided in the references cited.

In addition to inventory methods, it is also possible to estimate carbon sources and sinks by measuring carbon dioxide (CO_2) in the atmosphere. For example, if air exits the border of a continent with more CO_2 than it contained when it entered, then there must be a net source of CO_2 somewhere inside the continent. We do not include estimates obtained in this way because they are still highly uncertain at continental scales. Pacala *et al.* (2001) found that atmosphere- and inventory-based methods gave consistent estimates of United States' ecosystem sources and sinks but that the range of uncertainty from the former was considerably larger than the range from the latter. For example, by far the largest published estimate for the North American carbon sink was produced by an analysis of atmospheric data by Fan *et al.* (1998) (-1700 Mt C per year). The appropriate inventory-based estimate to compare this to is our -666 Mt C per year of net absorption (atmospheric estimates include net horizontal exports by rivers and trade), and this number is well within the wide uncertainty limits in Fan *et al.* (1998). The allure of estimates from atmospheric data is that they do not risk missing critical uninventoried carbon pools. But in practice, they are still far less accurate at continental scales than a careful inventory (Pacala *et al.*, 2001). Using today's technology, it should be possible to complete a comprehensive inventory of the sink at national scales with the same accuracy as the United States' forest inventory currently achieves for above-ground carbon in forests (25%, Smith and Heath, 2005). Moreover, this inventory would provide disaggregated information about the sink's causes and geographic distribution. In contrast, estimates from atmospheric methods rely on the accuracy of atmospheric models, and estimates obtained from different models vary by 100% or more at the scale of the United States, Canada, or Mexico (Gurney *et al.*, 2004). Nonetheless, extensions of the atmospheric sampling network should improve the accuracy of atmospheric methods and might allow them to achieve the accuracy of inventories at regional and whole-country scales. In addition, atmospheric methods will continue to provide an independent check on inventories to make sure that no large flux is missed, and atmospheric methods will remain the only viable method to assess interannual variation in the continental flux of carbon.

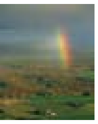


The current magnitude of the North American sink (documented in Tables 3.1 and 3.2) offers the possibility that significant carbon mitigation could be accomplished by managing forests, rangelands, and croplands to increase the carbon stored in them. However, many of the estimates in Tables 3.1 and 3.2 are highly uncertain; for some, the range of uncertainty is larger than the value reported. The largest contributors to the uncertainty in the United States' sink are the amount of carbon stored on rangelands because of the encroachment of woody vegetation and the lack of comprehensive and continuous inventory of Alaskan lands. A carbon inventory of these lands would do more to constrain the size of the United States' sink than would any other measurement program of similar cost. Also, we still lack

Table 3.2 Annual net horizontal transfers of carbon in millions of tons (see Box 3.1 for uncertainty conventions).

Net horizontal transfer: imports exceed exports = positive; exports exceed imports = negative	United States	Canada	Mexico	North America
Wood products	14[c]****	–74[a]****	–1[b]*	–61****
Agriculture products	–65[d]***	ND	ND	–65***
Rivers to ocean	–35[d]**	ND	ND	–35*
Total net absorption (Total carbon source or sink in Table 3.1 plus exports)	–575***	–138**	47*	–666**
Net absorption (negative) or emission (positive) by coastal waters	ND	ND	ND	19[e]*

[a] Environment Canada (2005), World Forest Institute (2006)
[b] Masera *et al.* (1997)
[c] Skog *et al.* (2004), Skog and Nicholson (1998)
[d] Pacala *et al.* (2001)
[e] Chapter 15
ND indicates that no data are available.



comprehensive United States' inventories of carbon in soils, woody debris, wetlands, rivers, and reservoirs. Finally, we lack estimates of any kind for five significant components of the carbon budget in Canada and six in Mexico (see Tables 3.1 and 3.2).

The cause and future of the North American carbon sink is also highly uncertain. Although we can document the accumulation of carbon in ecosystems and wood products, we do not know how much of the sink is due to fertilization of the ecosystems by the nitrogen in air pollution and by the added CO$_2$ in the atmosphere. We do not fully understand the impact of tropospheric ozone, nor do we understand precisely how the sink will change as the climate changes. Research is mixed about the importance of nitrogen and CO$_2$ fertilization (Casperson *et al.*, 2000; Oren *et al.*, 2001; Hungate *et al.*, 2003; Luo, 2006**;** Körner *et al.*, 2005). If these factors are weak, then, all else being equal, we expect the North American sink to decline over time as ecosystems complete their recovery from past exploitation (Hurtt *et al.*, 2002). However, if these factors are strong, then the sink could grow in the future. Similarly, global warming is expected to lengthen the growing season in most parts of North America, which should increase the sink (but see Goetz *et al.*, 2005). But warming is also expected to increase forest fire and the rate of decomposition of dead organic matter, which should decrease the sink and might convert it into a source (Gillett *et al.*, 2004; Flannigan *et al.*, 2005; Schaphoff *et al.*, 2006; Westerling *et al.*, 2006). The relative strength of the various opposing factors is still difficult to predict. Experimental manipulations of climate, atmospheric CO$_2$, tropospheric ozone, and nitrogen, at the largest possible scale, will be required to reduce uncertainty about the future of the carbon sink.

In what follows, we provide additional detail about the elements in Tables 3.1 and 3.2.

3.2.1 Forests

Based on U.S. Forest Service inventories, forest ecosystem carbon stocks in the United States, excluding soil carbon, have increased since 1953. The rate of increase has recently slowed because of increasing harvest and declining growth in some areas with maturing forests. The current average annual increase in carbon in trees is 146 Mt C per year (Smith and Heath, 2005, uncertainty ****) plus 20 Mt C per year from urban and suburban trees (the midpoint of the range in Chapter 14, uncertainty ***). The total estimate of the carbon sink in forested ecosystems is -256 Mt C per year and includes a sink of 90 Mt C per year (uncertainty **) from the accumulation of nonliving carbon in the soil (-90-146-20 = -256) (Pacala *et al.*, 2001; Goodale *et al.*, 2002). Although the magnitude of the forest soil sink has always been uncertain, it is now possible to measure the total above-and below-ground sink in a few square kilometers by monitoring the atmospheric CO$_2$ that flows into and out of the site over the course of a year. Note that these spatially intensive methods, appropriate for monitoring the sink over a few square kilometers, are unrelated to the spatially extensive methods described above, which attempt to constrain the sink at continental scales. As described in Appendix B, these studies are producing data that, so far, confirm the estimates of inventories and show that most of the forest sink is above-ground.

According to Canada's Greenhouse Gas Inventory (Environment Canada 2006, Chapter 11 this report), managed forests in Canada (comprising 83% of the total forest area) sequestered an average of 17 Mt C per year in trees and soils between 1990 and 2004 (uncertainty **). In addition, Chapter 14 estimates a sink of 11 (2-20) Mt C per year in urban and suburban trees of Canada (uncertainty ***) that were not included in the Environment Canada (2006) accounting. The total estimate for the Canadian forest sink is thus 28 Mt C per year (Table 3.1).

The two published carbon inventories for Mexican forests (Masera *et al.*, 1997 and Cairns *et al.*, 2000) both report substantial losses of forest carbon, primarily because of deforestation in the tropical south. However, both of these studies rely on calculations of carbon loss from remote imagery, rather than direct measurements, and both report results for a period that ended more than 10 years ago. Thus, in addition to being highly uncertain, the estimates for Mexican forests in Table 3.1 are not recent. Chapter 14 estimates a small urban forest sink of 2 (0-3) Mt C per year in Mexico. Whether the small urban forest sink would have been detected in changes in remote imagery and included in the Mexican inventories is uncertain, and accordingly is not included in Table 3.1.

3.2.2 Wood Products

Wood products create a carbon sink because they accumulate both in use (*e.g.*, furniture, house frames, *etc.*) and in landfills. The wood products sink is estimated at -57 Mt C per year in the United States (Skog and Nicholson, 1998) and

Table 3.3 Carbon stocks in North America in billions of tons, (see Box 3.1 for uncertainty conventions).

	United States	Canada	Mexico	North America
Forest	67^{a},***	86^{a},***	19^{d},**	171***
Cropland	14^{b},****	4^{b},****	1^{b},**	19****
Grazing lands	33^{b},***	12^{b},***	10^{b},***	55***
Wetlands	64^{c},***	157^{c},***	2^{c},*	223***
Total	178***	259***	33**	468***

[a] Goodale *et al.* (2002)
[b] Chapter 10
[c] Chapter 13
[d] Masera *et al.* (1997)

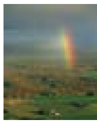
-11 Mt C per year in Canada (Goodale *et al*., 2002, Chapter 11 this report). We know of no estimates for Mexico.

3.2.3 Woody Encroachment

Woody encroachment is the invasion of woody plants into grasslands or the invasion of trees into shrublands. It is caused by a combination of fire suppression and grazing. Fire inside the United States has been reduced by more than 95% from the pre-settlement level of approximately 80 million hectares burned per year, and this favors shrubs and trees in competition with grasses (Houghton *et al*., 2000). Field studies show that woody encroachment both increases the amount of living plant carbon and decreases the amount of dead carbon in the soil (Guo and Gifford, 2002; Jackson *et al*., 2002). Although the total gains and losses are ultimately of similar magnitude (Jackson *et al*., 2002), the losses occur within approximately a decade after the woody plants invade (Guo and Gifford, 2002), while the gains occur over a period of up to a century or more. Thus, the net source or sink depends on the distribution of times since woody plants invaded, and this is not known. Estimates for the size of the current United States' woody encroachment sink (Houghton *et al*., 1999, Houghton and Hackler, 2000; and Hurtt *et al*., 2002) all rely on methods that do not account for the initial rapid loss of carbon from soil when grasslands were converted to shrublands or forest. The estimate of -120 Mt C per year in Table 3.1 is from Houghton *et al.* (1999), but is similar to the estimates from the other two studies (-120 and -130 Mt C per year). No estimates are currently available for Canada or Mexico. Note the error estimate of more than 100% in Table 3.1. A comprehensive set of measurements of woody encroachment would reduce the error in the national and continental carbon budgets more than any other inventory.

3.2.4 Agricultural Lands

Soils in croplands and grazing lands have been historically depleted of carbon by humans and their animals, especially if the land was converted from forest to non-forest use. Harvest or consumption by animals reduces the input of organic matter to the soil, while tillage and manure inputs increase the rate of decomposition. Changes in cropland management, such as the adoption of no-till agriculture (Chapter 10 this report), have reversed the losses of carbon on some croplands, but the losses continue on the remaining lands. The net is a small sink of -2 Mt C per year for agricultural soils in Canada and, for the United States, is a sink of between -5 and -12 Mt C per year.



3.2.5 Wetlands

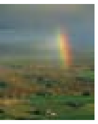
Peatlands are wetlands that have accumulated deep soil carbon deposits because plant productivity has exceeded decomposition over thousands of years. Thus, wetlands form the largest carbon pool of any North American ecosystem (Table 3.3). If drained for development, this soil carbon pool is rapidly lost. Canada's extensive frozen and unfrozen wetlands create a net sink of -23 Mt C per year, with from -6 to -11 Mt C per year of that sink in areas underlain by permafrost (Chapters 12 and 13, this report). Drainage of peatlands in the conterminous United States has created a source of 6 Mt C per year, but other wetlands, including those in Alaska, are a sink of -29 Mt C per year for a net United States wetland sink of -23 Mt C per year (Chapter 13, this report). The very large pool of peat in northern wetlands is vulnerable to climate change and could add more than 100 ppm to the atmosphere (1 ppm ≈ 2.1 billion tons of carbon [Gt C]) during this century, if released, because of global warming (see the model result in Cox *et al*., 2000 for an example).

> Wetlands form the largest carbon pool of any North American ecosystem (Table 3.3). If drained for development, this soil carbon pool is rapidly lost.

The carbon sink due to sedimentation in wetlands is estimated to be 4 Mt C per year in Canada and 22 Mt C per year in the United States,

but this estimate is highly uncertain (Chapter 13 this report). Another important priority for research is to better constrain carbon sequestration due to sedimentation in wetlands, lakes, reservoirs, and rivers.

The focus on this chapter is on CO_2; we do not include estimates for other greenhouse gases. However, wetlands are naturally an important source of methane (CH_4). Methane emissions effectively cancel out the positive benefits of any carbon storage, such as peat in Canada, and make United States' wetlands a source of warming on a decadal time scale (Chapter 13 this report). Moreover, if wetlands become warmer and remain wet with future climate change, they have the potential to emit large amounts of CH_4. This is probably the single most important consideration, and unknown, in the role of wetlands and future climate change.



3.2.6 Rivers and Reservoirs

Organic sediments accumulate in artificial lakes and in alluvium (deposited by streams and rivers) and colluvium (deposited by wind or gravity) and represent a carbon sink. Pacala *et al.* (2001) extended an analysis of reservoir sedimentation (Stallard, 1998) to an inventory of the 68,000 reservoirs in the United States and also estimated net carbon burial in alluvium and colluvium. Table 3.1 includes the midpoint of their estimated range of 10 to 40 Mt C per year in the coterminous United States. This analysis has also recently been repeated and produced an estimate of 17 Mt C per year (E. Sundquist, personal communication; unreferenced). We know of no similar analysis for Canada or Mexico.

3.2.7 Exports Minus Imports of Wood and Agricultural Products

The United States imports more wood products (14 Mt C per year) than it exports and exports more agricultural products (35 Mt C per year) than it imports (Pacala *et al.*, 2001). The large imbalance in agricultural products is primarily because of exported grains and oil seeds. Canada and Mexico are net wood exporters, with Canada at -74 Mt C per year (Environment Canada, 2005) and Mexico at -1 Mt C per year (Masera *et al.*, 1997). The North American export of 61 Mt C per year accounts correctly for the large net transfer of lumber and wood products from Canada to the United States. We know of no analysis of the Canadian or Mexican export-import balance for agricultural products.

Fossil-fuel emissions currently dominate the net carbon balance in the United States, Canada, and Mexico.

3.2.8 River Export

Rivers in the coterminous United States were estimated to export 30-40 Mt C per year to the oceans in the form of dissolved and particulate organic carbon and inorganic carbon derived from the atmosphere (Pacala *et al.*, 2001). An additional 12-20 Mt C per year of inorganic carbon is also exported by rivers but is derived from carbonate minerals. We know of no corresponding estimates for Alaska, Canada, or Mexico.

3.2.9 Coastal Waters

Chapter 15 summarizes the complexity and large uncertainty of the sea-air flux of CO_2 in North American coastal waters. It is important to understand that the source in Mexican coastal waters is not caused by humans and would have been present in pre-industrial times. It is simply the result of the purely physical upwelling of carbon-rich deep waters and is a natural part of the oceanic carbon cycle. It is not yet known how much of the absorption of carbon by United States' and Canadian coastal waters is natural and how much is caused by nutrient additions to the coastal zone by humans. Accordingly, it is essentially impossible to currently assess the potential or costs of carbon management in coastal waters of North America.

3.3 SUMMARY

Fossil-fuel emissions currently dominate the net carbon balance in the United States, Canada, and Mexico (Figure 3.1, Tables 3.1 and 3.2). In 2003, fossil-fuel consumption in the United States emitted 1582 Mt C per year to the atmosphere (confidence ****, see definition of confidence categories in Table 3.1 footnote). This source was partially balanced by a flow of 489 Mt C per year from the atmosphere to land caused by net ecosystem sinks in the United States (***). Canadian fossil-fuel consumption transfered 164 Mt C per year to the atmosphere in 2003 (****), but net ecological sinks capture 64 Mt C per year (**). Mexican fossil-fuel emissions of 110 Mt C per year (****) were supplemented by a net ecosystem source of 48 Mt C per year (*) from tropical deforestation. Each of the three countries has always been a net source of CO_2 emissions to the atmosphere for the past three centuries (Houghton *et al.*, 1999, 2000; Houghton and Hackler, 2000; Hurtt *et al.*, 2002).

CHAPTER 4

What Are the Options That Could Significantly Affect the North American Carbon Cycle?

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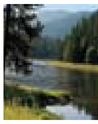

KEY FINDINGS

- Options to reduce energy-related carbon dioxide emissions include improved efficiency, fuel switching (among fossil fuels and non-carbon fuels), and carbon dioxide capture and storage.
- Most energy use, and hence energy-related carbon dioxide emissions, involves equipment or facilities with a relatively long life—5 to 50 years. Many options for reducing these carbon dioxide emissions are most cost-effective, and sometimes only feasible, in new equipment or facilities. This means that cost-effective reduction of energy-related carbon dioxide emissions may best be achieved as existing equipment and facilities are replaced[1]. If emission reductions are implemented over a long time, technological change will have a significant impact on the cost.
- Options to increase carbon sinks include forest growth and agricultural soil sequestration. The amount of carbon that can be captured by these options is significant, but additions to current stocks would be small to moderate relative to carbon emissions. These options can be implemented in the short term, but the amount of carbon sequestered typically is low initially, then rises for a number of years before tapering off again as the total potential is achieved. There is also a significant risk that the carbon sequestered may be released again by natural phenomena or human activities.
- Both policy-induced and voluntary actions can help reduce carbon emissions and increase carbon sinks, but significant changes in the carbon budget are likely to require policy interventions. The effectiveness of a policy depends on the technical feasibility and cost-effectiveness of the portfolio of actions it seeks to promote, on its suitability given the institutional context, and on its interaction with policies implemented to achieve other objectives.
- Policies to reduce atmospheric carbon dioxide concentrations cost effectively in the short- and long-term could include: (1) encouraging adoption of cost-effective emission reduction and sink enhancement actions through such mechanisms as an emissions trading program or an emissions tax; (2) stimulating development of technologies that lower the cost of emissions reduction, carbon capture and sequestration, and sink enhancement; (3) adopting appropriate regulations for sources or actions subject to market imperfections, such as energy efficiency measures and cogeneration; (4) revising existing policies with other objectives that lead to higher carbon dioxide or methane emissions so that the objectives, if still relevant, are achieved with lower emissions; and (5) encouraging voluntary actions.
- Implementation of such policies at a national level, and cooperation at an international level, would reduce the overall cost of achieving a carbon reduction target by providing access to more low-cost mitigation/sequestration options.

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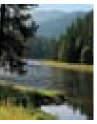
[1] An emission reduction action is cost-effective if the cost per ton of carbon dioxide reduced is lower than the least-cost alternative.

4.1 INTRODUCTION

This chapter provides an overview of options that can reduce carbon dioxide (CO_2) and methane (CH_4) emissions and those that can enhance carbon sinks, and it attempts to compare them. Finally, it discusses policies to encourage implementation of source reduction and sink enhancement options. No emission reduction or sink enhancement target is proposed, and no policy or option is recommended.

4.2 SOURCE REDUCTION OPTIONS

4.2.1 Energy-Related Carbon Dioxide Emissions



Combustion of fossil fuels is the main source of CO_2 emissions (Chapters 1-3 this report), although some CO_2 is also released in non-combustion and natural processes. Most energy use, and hence energy-related CO_2 emissions, involves equipment or facilities with a relatively long life—5 to 50 years. Many options for reducing these CO_2 emissions are most cost-effective, and sometimes only feasible, in new equipment or facilities (Chapters 6 through 9 this report).

Canada and the United States use much more energy *per capita* than other high income countries, suggesting considerable potential to reduce energy use and associated CO_2 emissions with little impact on the standard of living.

To stabilize the atmospheric concentration of CO_2 "would require global anthropogenic CO_2 emissions to drop below 1990 levels . . . and to steadily decrease thereafter" (IPCC, 2001)[2]. That entails a transition to a very different energy system, for example, where the major energy carriers are electricity and hydrogen produced by non-fossil sources or from fossil fuels with capture and geological storage of the CO_2 generated. A transition to such an energy system, while also meeting growing energy needs, could take at least several decades. Thus, shorter term (2015–2025) and longer term (post-2050) options are differentiated.

Options to reduce energy-related CO_2 emissions can be grouped into a few categories:

- efficiency improvement,
- fuel switching to fossil fuels with lower carbon content per unit of energy produced or to non-fossil fuels, and
- switching to electricity and hydrogen produced from fossil fuels in processes with CO_2 capture and geological storage.

4.2.1.1 Efficiency Improvement

Energy is used to provide services such as heat, light, and motive power. Any measure that delivers the desired service with less energy is an efficiency improvement[3]. Efficiency improvements reduce CO_2 emissions whenever they reduce the use of fossil fuels at any point between production of the fuel and delivery of the desired service[4]. Energy use can be reduced by improving the efficiency of individual devices (such as refrigerators, industrial boilers, and motors), by improving the efficiency of systems (using the correct motor size for the task), and by using energy that is not currently utilized, such as waste heat[5]. Opportunities for efficiency improvements are available in all sectors.

It is useful to distinguish two levels of energy efficiency improvement: (1) the amount consistent with efficient utilization of resources (the economic definition) and (2) the maximum attainable (the engineering definition). Energy efficiency improvement thus covers a broad range, from measures that provide a cost saving to measures that are technically feasible but too expensive under current market conditions to warrant implementation. Market imperfections inhibit adoption of some cost-effective efficiency improvements (NCEP, 2005)[6].

Energy efficiency improvements tend to occur gradually, but steadily, across the economy in response to technological developments, replacement of equipment and buildings, changes in energy prices, and other factors[7]. In the short term, the potential improvement depends largely on greater deployment and use of available efficient equipment and technology. In the long term, it depends largely on tech-

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[2] The later the date at which global anthropogenic CO_2 emissions drop below 1990 levels, the higher the level at which the CO_2 concentration is stabilized.

[3] In the transportation sector, for example, energy efficiency can be increased by improving the fuel performance of vehicles, shifting to less emissions-intensive modes of transport, and adopting options that reduce transportation demand, such as telecommuting and designing communities so that people live closer to shopping and places of work.

[4] Increasing the fuel economy of vehicles or the efficiency of coal-fired generating units reduces fossil-fuel use directly. Increasing the efficiency of refrigerators or electricity transmission reduces electricity use and hence the fossil fuel used to generate electricity.

[5] For example, 40 to 70% of the energy in the fuel used to generate electricity is wasted. Cogeneration or combined heat and power systems generate electricity and produce steam or hot water. Cogeneration requires a nearby customer for the steam or heat.

[6] Examples of market imperfections include limited foresight, externalities, capital market barriers, and principal/agent split incentive problems. As an example of the principal/agent imperfection, a landlord has little incentive to improve the energy efficiency of the housing unit and its appliances if the tenant pays the energy bills.

[7] The rate of efficiency improvement varies widely across different types of equipment such as lighting, refrigerators, electric motors, and motor vehicles.

nological developments. Canada and the United States use much more energy *per capita* than other high-income countries, suggesting considerable potential to reduce energy use and associated CO_2 emissions with little impact on the standard of living[8].

4.2.1.2 Fuel Switching

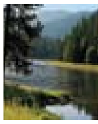
Energy-related CO_2 emissions are primarily due to combustion of fossil fuels. Thus CO_2 emissions can be reduced by switching to a less carbon-intensive fossil fuel or to a non-carbon fuel.

The CO_2 emissions per unit of energy (carbon intensity) for fossil fuels differ significantly, with coal being the highest, oil and related petroleum products about 25% lower, and natural gas over 40% lower than coal. Oil and/or natural gas can be substituted for coal in all energy uses, mainly electricity generation. However, natural gas is not available everywhere in North America and is much less abundant than coal, limiting the large-scale, long-term replacement of coal with natural gas. Technically, natural gas can replace oil in all energy uses, but to substitute for gasoline and diesel fuel, by far the largest uses of oil, would require conversion of millions of vehicles and development of a gas-refueling infrastructure.

Non-fossil fuels include

- biomass and fuels, such as ethanol and biodiesel, produced from biomass; and
- electricity and hydrogen produced from carbon-free sources.

Biomass can be used directly as a fuel in some situations. Pulp and paper plants and sawmills, for example, can use wood waste and sawdust as fuel. Ethanol, currently produced mainly from corn, is blended with gasoline and biodiesel is produced from vegetable oils and animal fats. Wood residuals and cellulose materials, such as switch grass, can be utilized both for energy and the production of syngases, which can be used to produce biopetroleum (AF&PA, 2006). The CO_2 emission reduction achieved depends on whether the biomass used is replaced, on the emissions associated with production and combustion of the biomass fuel, and the carbon content of the fuel displaced[9].



Carbon-free energy sources include hydro, wind, solar, biomass, geothermal, and nuclear fission[10]. Sometimes they are used to provide energy services directly, such as solar water heating and windmills for pumping water. But they are mainly used to generate electricity, about 35% of the electricity in North America. Currently, generating electricity using any of the carbon free energy sources is usually more costly than using fossil fuels.

Most of the fuel switching options are currently available, and so are viable short-term options in many situations.

4.2.1.3 Electricity and Hydrogen From Fossil Fuels with Carbon Dioxide Capture and Storage

About 65% of the electricity in North America is generated from fossil fuels, mainly coal, but with a rising share for natural gas (EIA, 2003a; Chapter 6 this report). The CO_2 emissions from fossil-fired generating units can be captured and injected into a suitable geological formation for long-term storage.

Hydrogen (H_2) is an energy carrier that emits no CO_2 when burned, but may give rise to CO_2 emissions when it is produced (National Academies, 2004). Currently, most hydrogen is produced from fossil fuels in a process that generates CO_2 (National Research Council, 2004). The CO_2 from this process can be captured and stored in geological formations. Alternatively, hydrogen can be produced from water using electricity, in which case the CO_2 emissions depend on how the electricity is generated. Hydrogen could substitute for

> Carbon-free energy sources include hydro, wind, solar, biomass, geothermal, and nuclear fission. Combined these sources generate about 35% of the electricity in North America.

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[8] The total primary energy supply *per capita* during 2004, in tons of oil equivalent, was 8.42 for Canada, 7.91 for the United States, 4.43 for France, 4.22 for Germany, 4.18 for Japan, 3.91 for the United Kingdom, and 1.59 for Mexico (IEA, 2006a).

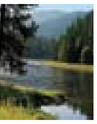
[9] The CO_2 reductions achieved depend on many factors including the inputs used to produce the biomass (fertilizer, irrigation water), whether the land is existing cropland or converted from forests or grasslands, and the management practices used (no-till, conventional till).

[10] Reservoirs for hydroelectric generation produce CO_2 and CH_4 emissions, and production of fuel for nuclear reactors generates CO_2 emissions, so such sources are not totally carbon free.

natural gas in most energy uses and could be used by fuel cell vehicles.

Carbon dioxide can be captured from the emissions of large sources, such as power plants, and pumped into geologic formations for long-term storage, thus permitting continued use of fossil fuels while avoiding CO_2 emissions to the atmosphere[11]. Many variations on this basic theme have been proposed; for example, pre-combustion vs. post-combustion capture, production of hydrogen from fossil fuels, and the use of different chemical approaches and potential storage reservoirs (IPCC, 2005). While most of the basic technology exists, legal, environmental, and safety issues need to be addressed before CO_2 capture and storage can be integrated into our energy system, so this is mainly a long-term option (IPCC, 2005). Carbon dioxide capture and storage could contribute about 30% (15-55%) of the total mitigation effort, mainly after 2025 (IPCC, 2005; IEA, 2006b; Stern, 2006).

CO_2 capture and storage could contribute about 30% of the total mitigation effort, mainly after 2025.



4.2.2 Industrial Processes

The processes used to make cement, lime, and ammonia release CO_2. Because the quantity of CO_2 released is determined by chemical reactions, the process emissions are determined by the output. But the CO_2 could be captured and stored in geological formations. Carbon dioxide also is released when iron ore and coke are heated in a blast furnace to produce molten iron, but alternative steel-making technologies with lower CO_2 emissions are commercially available. Consumption of the carbon anodes during aluminum smelting leads to CO_2 emissions, but good management practices can reduce the emissions. Raw natural gas contains CO_2 that is removed at gas processing plants and could be captured and stored in geological formations.

4.2.3 Methane Emissions

Methane is produced as organic matter decomposes in low-oxygen conditions and is emitted by landfills, wastewater treatment plants, and livestock manure. In many cases, the CH_4 can be collected and used as an energy source. Methane emissions also occur during the transport of natural gas. Such emissions usually can be flared or collected for use as an energy source[12]. Ruminant animals produce CH_4 while digesting their food. Emissions by ruminant farm animals can be reduced by measures that improve animal productivity. All of these emission reduction options are currently available.

Forest growth and soil sequestration currently offset about 30% of the North American fossil-fuel emissions.

4.3 TERRESTRIAL SEQUESTRATION OPTIONS

Trees and other plants sequester carbon as biological growth captures carbon from the atmosphere and sequesters it in the plant cells (IPCC, 2000). Currently, very large volumes of carbon are sequestered in the plant cells of the Earth's forests. Increasing the stock of forest through afforestation[13], reforestation, or forest management draws carbon from the atmosphere and increases the carbon sequestered in the forest and the soil of the forested area. Sequestered carbon is released by fire, insects, disease, decay, wood harvesting, conversion of land from its natural state, and disturbance of the soil. Substituting long-lived wood products for steel and cement can reduce emissions and increase the amount of carbon sequestered.

Agricultural practices can increase the carbon sequestered by the soil. Some crops build soil organic matter, which is largely carbon, better than others. Some research shows that crop-fallow systems result in lower soil carbon content than continuous cropping systems (Chapter 10 this report). No-till and low-till cultivation builds soil organic matter.

Conversion of agricultural land to forestry can increase carbon sequestration in soil and tree biomass, but the rate of sequestration depends on environmental factors (such as type of trees planted, soil type, climate, and topography) and management practices (such as thinning, fertilization, and pest control). Conversion of agricultural land to other uses can result in positive or negative net carbon emissions depending upon the land use.

Forest growth and soil sequestration currently offset about 30% (15-45%) of the North American fossil fuel emissions (Chapter 3 this report), and this percentage might be increased to some degree. These options can be implemented in the short term, but the amount of carbon sequestered typically is low initially, then rises for a number of years before tapering off again as the total potential is achieved (Chapters 10-13 this report).

4.4 INTEGRATED COMPARISON OF OPTIONS

As is clear from the previous sections, there are many options to reduce emissions of or to sequester CO_2. To help them decide which options to implement, policy makers need to

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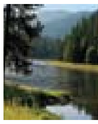
[11] Since combustion of biomass releases carbon previously removed from the atmosphere, capture and storage of these emissions results in negative emissions (a sink).

[12] Flaring or combustion of CH_4 as an energy source produces CO_2 emissions.

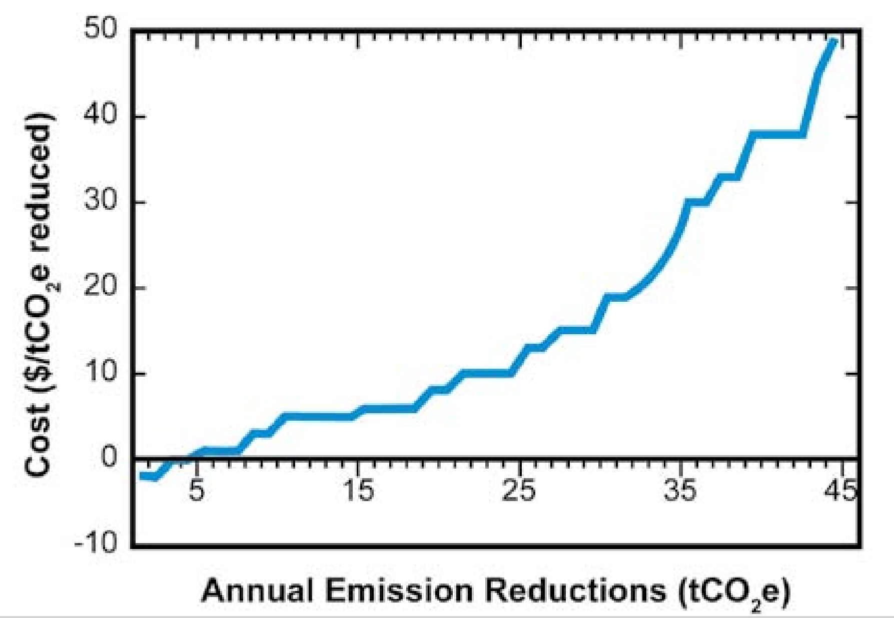
[13] See the *Glossary* for a definition of this term and related terms.

BOX 4.1: Emission Reduction Supply Curve

A tool commonly used to compare emission reduction and sequestration options is an emission reduction supply curve, such as that shown in the figure. It compiles the emission reduction and sequestration options available for a given jurisdiction at a given time. If the analysis is for a future date, a detailed scenario of future conditions is needed. The estimated emission reduction potential of each option is based on local circumstances at the specified time, taking into account the interaction among options, such as improved fuel efficiency for vehicles and greater use of less carbon-intensive fuel. The options are combined into a curve starting with the most cost-effective and ending with the least cost-effective. For each option, the curve shows the cost per metric ton of CO_2 reduced on the vertical axis and the potential emission reduction, tons of CO_2 per year, on the horizontal axis. The curve can be used to identify the lowest cost options to meet a given emission reduction target, the associated marginal cost (the cost per metric ton of the last option included), and total cost (the area under the curve).



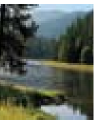
An emission reduction supply curve is an excellent tool for assessing alternative emission reduction targets. The best options and cost are easy to identify. The effect on the cost of dropping some options is easy to calculate unless they interact with other options. And the cost impact of having to implement additional options due to underperformance by others is simple to estimate. The drawbacks are that constructing the curve is a complex analytical process and that the curve is out of date almost immediately because fuel prices and the cost or performance of some options change.



The curve shows the estimated unit cost ($/t CO_2 equivalent) and annual emission reduction (t CO_2 equivalent) for emission reduction and sequestration options for a given region and date arranged in order of increasing unit cost.

When constructed for a future date, such as 2010 or 2020, the precision suggested by the curve is misleading because the future will differ from the assumed scenario. A useful approach in such cases is to group options into cost ranges, such as less than $5 per metric ton of CO_2, $5 to $15 per metric ton of CO_2, etc., ignoring some interaction effects and the impacts of the policy used to implement the option. This still identifies the most cost-effective options. Comparing the emissions reduction target with the emission reduction potential of the options in each group indicates the most economic strategy.

know the magnitude of the potential emission reduction at various costs for each option so they can select the options that are the most cost-effective—have the lowest cost per metric ton of CO_2 reduced or sequestered.



This involves an integrated comparison of options, which can be surprisingly complex in practice. It is most useful and accurate for short-term options where the cost and performance of each option can be forecast with a high degree of confidence. The performance of many options is interrelated; for example, the emission reductions that can be achieved by blending ethanol in gasoline depend, in addition to the factors relating to ethanol production previously cited, on other options, such as telecommuting to reduce travel demand, the success of modal shift initiatives, and the efficiency of motor vehicles. The prices of fossil fuels affect the cost-effectiveness of many options. Finally, the policy enacted to encourage an option, incentives vs. a regulation for example, can affect its potential.

The emission reduction potential and cost-effectiveness of options also vary by location. Energy sources and sequestration options differ by location; for example, natural gas may not be available, the wind and solar regime vary, hydro potential may be small or large, land suitable for afforestation/reforestation is limited, the agricultural crops may or may not be well suited to low-till cropping. Climate, lifestyles, and consumption patterns also affect the potential of many options; for example, more potential for heating options in a cold climate or air conditioning options in a hot climate. The mix of single-family and multi-residential buildings affects the potential for options focused on those building types, and the scope for public transit options tends to increase with city size. Institutional factors affect the potential of many options as well; for example, the prevalence of rented housing affects the potential to implement residential emission reduction measures, the authority to specify minimum efficiency standards for vehicles, appliances, and equipment may rest with the state/provincial government or the national government, and the ownership and regulatory structure for gas and electric utilities can affect their willingness to offer energy efficiency programs.

The estimated cost and emission reduction potential for the principal short-term CO2 emission reduction and sequestration options are summarized in Table 4.1. All estimates are expressed in 2004 United States dollars per metric ton of carbon . The limitations of emission reduction supply curves noted in the text box apply equally to the cost estimates in Table 4.1.

Most options have a range of costs. The range is due to four factors. First, the cost per unit of emissions reduced varies by location even for a very simple measure. For example, the emission reduction achieved by installing a more efficient light bulb depends on the hours of use and the generation mix that supplies the electricity. Second, the cost and performance of any option in the future is uncertain. Different assumptions about future costs and performance contribute to the range. Third, most mitigation and sequestration options are subject to diminishing returns, that is, their cost rises at an increasing rate with greater use, as in the power generation, agriculture, and forestry cost estimates[14]. So the estimated scale of adoption contributes to the range. Finally, some categories include multiple options, notably those for the United States economy as a whole, each with its own marginal cost. For example, the "All Industry" category is an aggregation of seven subcategories discussed in Chapter 8 this report. The result again is a range of cost estimates.

The cost estimates in Table 4.1 are the direct costs of the options. A few options, such as the first estimate for power generation in Table 4.1, have a negative annualized cost. This implies that the option is likely to yield cost savings for reasons such as improved combustion efficiency. Some options have ancillary benefits (*e.g.*, reductions in ordinary pollutants, reduced dependence on imported oil, expansion of wildlife habitat associated with afforestation) that reduce their cost from a societal perspective. Indirect (multiplier, general equilibrium, macroeconomic) effects in the economy tend to increase the direct costs (as when the increased cost of energy use raises the price of products that use energy or energy-intensive inputs). Examples of these complicating effects are presented in Chapters 6 through 11 this report, along with some estimates of their impacts on costs.

None of the options listed in Table 4.1 offers the prospect of carbon budget stabilization alone (see below), which indicates a need to consider combinations of options. In any such consideration, costs are the primary driving force (*e.g.*, Table 4.1). Other considerations affecting the choice of options include the magnitudes of their potential contributions, their feasibility, and the time scale of their contribution. Table 4.2 summarizes these characteristics for the main families of emission reduction and sink enhancement options (see also Kauppi *et al*., 2001).

As indicated in several segments of Table 4.1, costs are sensitive to the policy instruments used to encourage the option. In general, the less restrictive the policy, the lower the cost. That is why the cost estimates for the Feebate[15] are lower than the cost estimate for the Corporate Average Fuel Economy (CAFE) standard. In a similar vein, costs are low-

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[14] For example, increasing the scale of tree planting to sequester carbon requires more land. Typically, the value of the extra land used rises, so the additional sequestration becomes increasingly costly.

[15] A "Feebate" is a system of progressive vehicle taxes on purchases of less efficient new vehicles and subsidies for more efficient new vehicles.

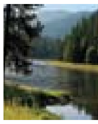
Table 4.1 Standardized cost estimates for short-term CO_2 emission reduction and sequestration options (annualized cost in 2004 constant U.S. dollars per metric ton of carbon [t C]).

Option/applicable date(s)	Annualized average cost (in $2004 U.S.)	Potential range (Mt C per year) or % reduction	Source
Power generation	-$227 to 1176/tC	N.A.	DOE/EIA (2006)
Transportation/2010 (U.S. permit trading)	$84/t C	N.A.	EIA (2003b)
Transportation/2025 (U.S. permit trading)	$236/t C	22	EIA (2003b)
Transportation/2017 (CAFE standard[a])	$82/t C	39	CBO (2003)
Transportation/2030 (Feebate[b])	$47/t C	67	Greene *et al.* (2005)
Buildings	N.A.	60% for offices 70% for homes	USGBC (2005) DOE/EERE (2006)
Afforestation/2010-2110	$60 to 120/t C	37 to 224	EPA (2005)
Forest management/2010-2110	$4 to 120/t C	7 to 86	
Biofuels/2010-2110	$120 to 201/t C	102 to 153	
Agricultural soil carbon sequestration/2010-2110	$20 to 60/t C	34 to 46	
All industry			
Reduction of fugitives	$92 to 180/t C	3%	Herzog (1999) Martin *et al.* (2001) Jaccard *et al.* (2002, 2003a, 2003b) Worrel *et al.* (2004) DOE (2006)
Energy efficiency	$0 to 180/t C	8% to 12%	
Process change	$92 to 180/t C	20%	
Fuel substitution	$0 to 92/t C	10%	
CO_2 capture and storage	$180 to 367/t C	30%	
Waste management			
Reduction of fugitives	$0 to 92/t C	90%	Herzog (1999) Jaccard *et al.* (2002)
CO_2 capture and storage	>$367/t C	30%	
Entire U.S. economy			
No trading	$102 to 548/t C[c]	Not specified	EMF (2000)
Industrialized country trading	$19 to 299/t C[c]	Not specified	
Global trading	$7 to 164/t C[c]	Not specified	

[a] CAFE= Corporate Average Fuel Economy

[b] A "feebate" is a system of progressive vehicle taxes on purchases of less efficient new vehicles and subsidies for more efficient new vehicles.

[c] Annualized marginal cost (cost at upper limit of application, and therefore typically higher than average cost).



ered by expanding the number of participants in an emissions trading arrangement, especially those with a prevalence of low-cost options, such as developing countries. That is why global trading costs are lower than the industrialized country trading case for the United States economy.

The task of choosing the "best" combination of options may seem daunting given the numerous options, their associated cost ranges, and ancillary impacts. This combination will depend on several factors including the emission target, the emitters covered, the compliance period, and the ancillary benefits and costs of the options. The best combination will change over time as locations where cheap options can be implemented are exhausted, and technological change lowers the costs of more expensive options. It is unlikely that decision makers can identify the least-cost combination of options to achieve a given emission target, but they can adopt policies, such as emissions trading or emissions

Table 4.2 Overview of possible contributions of families of options to managing the North American carbon cycle.[a] Note that combining a number of small contributions can add up to a moderate contribution, and combining a number of moderate contributions can sdd up to a large contribution.

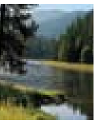
Category of Options	Magnitude of potential contribution	Feasibility of contribution	Time scale of contribution
Emission reduction			
Efficiency improvement	Moderate	High	Near to mid term
Fuel switching:			
- to less carbon-intensive fossil fuels	Small to moderate	High	Near to mid term
- to non-fossil fuels	Moderate to large	Moderate to high	Mid to long term
CO_2 capture and storage	Large[1]	Highly uncertain[2]	Long term[3]
Sink enhancement			
Forests	Small to moderate	Moderate to high	Near to mid term
Soils	Small	Moderate to high	Mid to long term

[a] Magnitude refers to the potential size of contribution in net emission reduction: large = above 500 MtC yr^{-1}; moderate = 250-500; small = below 250. Feasibility refers to the likelihood that such a magnitude can be reached under reasonable assumptions about economic, policy, and science/technology conditions. Time scale is defined as: long term = beyond 2040; mid term = 2020-2040; near term = sooner than 2020. Following principles of analytic-deliberative assessment (Stern and Fineberg, 1996), these categories represent the authors' expert synthesis and qualitative assessment or interpretation of diverse information presented or cited in this and other chapters of this report as well as from relevant literature (*e.g.*, IPCC, 2005; Kauppi *et al.*, 2001).

[1] Depending upon the (uncertain) availability of large geological reservoirs the potential contribution could possibly be very large (much greater than 500 Mt C per year).

[2] Uncertainty in availability of reservoirs, technology, public risk perception and costs among other factors makes the feasibility of large scale applications capable of realizing large potential highly uncertain.

[3] For large-scale or large-magnitude contributions exceeding the small magnitude, near term contributions of pilot-studies or existing oil recovery applications.



taxes, that cover a large number of emitters and allow them to use their first-hand knowledge to choose the lowest cost reduction options[16].

4.5 IMPLEMENTATING OPTIONS

4.5.1 Overview

No single technology or approach can achieve a sufficiently large CO_2 emission reduction or sequestration to stabilize the carbon cycle (Hoffert *et al*., 1998, 2002; Pacala and Socolow, 2004). Decision makers will need to consider a portfolio of options to reduce emissions and increase sequestration in the short term, taking into account constraints on and implications of mitigation strategies and policies. The portfolio of short-term options is likely to include greater efficiency in the production and use of energy; expanded use of non-carbon and low-carbon energy technologies; and various changes in forestry, agricultural, and land-use practices. Actions will also be supported by encouraging research and development of technologies that can reduce emissions even further in the long term, such as technologies for removing carbon from fossil fuels and sequestering it in geological formations and possibly other approaches, some of which are currently very controversial, such as certain types of "geoengineering."

No single technology or approach can achieve a sufficiently large CO_2 emission reduction or sequestration to stabilize the carbon cycle.

Because CO_2 has a long atmospheric residence time[17], immediate action to reduce emissions and increase sequestration allows its atmospheric concentration to be stabilized at a lower level[18]. Policy instruments to promote cost-effective implementation of a portfolio of options covering virtually all emissions sources and sequestration options are available for the short term. Implementation of policy instruments at a national level, and cooperation at an international level, would reduce the overall cost of achieving a carbon reduction target by providing access to more low-cost mitigation/sequestration options.

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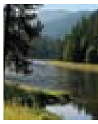
[16] Swift (2001) finds that emissions trading programs yield greater environmental and economic benefits than regulations. Several other studies of actual policies (Ellerman *et al*., 2000) and proposed policies (Rose and Oladosu, 2002) have indicated relative cost savings of these incentive-based instruments.

[17] Carbon dioxide has an atmospheric lifetime of 5 to 200 years. A single lifetime can not be defined for CO_2 because of different rates of uptake by different removal processes. (IPCC, 2001, Table 1, p. 38)

[18] IPCC (2001), p. 187.



The effectiveness of such policies is determined by the technical feasibility and cost-effectiveness of the portfolio of options they seek to promote, their interaction with other policies that have unintended impacts on CO_2 emissions, and their suitability given the institutional and socioeconomic context (Raupach *et al*., 2004). This means that the effectiveness of the portfolio can be limited by factors such as:

- Demographic and social dynamics. Land tenure, population growth, and migration may pose an obstacle to afforestation/reforestation strategies.
- Institutional settings. The acceptability of taxes, subsidies, and regulations to induce the deployment of certain technology may be limited by stakeholder opposition.
- Environmental considerations. The portfolio of options may incur environmental costs such as nuclear waste disposal or biodiversity reduction.
- Institutional and timing aspects of technology transfer. The patent system, for instance, may pose a barrier for some countries and sectors in obtaining the best available technology.

4.5.2 General Considerations

Decisions about the implementation of options for carbon management are made at a variety of geographic scales, by a variety of decision makers, for a variety of reasons. In many cases, they emphasize decentralized voluntary decision-making within market and other institutional conditions that are shaped by governmental policies. Over the past decade in the United States, state and local governments and private firms, motivated by such factors as cost savings, public image, and perceptions of possible future policy directions, have implemented voluntary actions to reduce CO_2 emissions (Kates and Wilbanks, 2003). Although these actions have contributed to a decline in the ratio of CO_2 emissions to GDP (Casler and Rose, 1998), total emissions have continued to increase.

A wide array of policies have been implemented or are under discussion by governments in North America[19]. Policies to encourage reduction and sequestration of CO_2 emissions could include information programs, voluntary programs, conventional regulation, emissions trading, and emissions taxes (Tietenberg, 2000). Working Group III of the Intergovernmental Panel on Climate Change (IPCC) concluded that "[V]oluntary agreements between industry and governments, which vary considerably, are politically attractive, raise awareness among stakeholders, and have played a role in the evolution of many national policies. . . However, there is little evidence that voluntary agreements have achieved significant emissions reductions beyond business as usual (high agreement/much evidence)." (Gupta *et al*. 2007; see also OECD, 2003b; Harrison, 1999; King and Lenox, 2000; Welch *et al*., 2000; Darnall and Carmin, 2003; Croci, 2005; Jaccard *et al*., 2006).

Reducing annual emissions in North America consistently over several decades requires a portfolio of policies across all sectors and gases tailored to fit specific national circumstances. Regulations can require designated sources to keep their emissions below a specified limit, either a quantity per unit of output or an absolute amount per day or year. Regulations can also stipulate minimum or average levels of energy efficiency of appliances, buildings, equipment, and vehicles.

Although voluntary actions have contributed to a decline in the ratio of CO_2 emissions to GDP, total emissions have continued to increase.

An emissions trading program establishes a cap on the annual emissions of a set of sources. Allowances equal to the cap are issued and can be traded. Each source must monitor its actual emissions and remit allowances equal to its actual emissions to the regulator. An emission trading program creates an incentive for sources with low-cost options to reduce their emissions and sell their surplus allowances. Sources with high-cost options find it less expensive to buy allowances at the market price than to reduce their own emissions enough to achieve compliance.

An emissions tax requires designated sources to pay a specified levy for each unit of its actual emissions. Each emitter will reduce its emissions to the point where the mitigation

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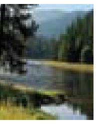
[19] Policies can be found at: http://www.epa.gov/climatechange/policy/neartermghgreduction.html, http://www.ecoaction.gc.ca/index-eng.cfm, and http://cambio_climatico.ine.gob.mx/ccygob/ccygobingles.html



cost is equal to the tax, but once the mitigation cost exceeds the tax, the emitter will opt to pay the tax.

The framework for evaluating such a policy instrument needs to consider technical, institutional, and socioeconomic constraints that would affect its implementation, such as the ability of sources to monitor their actual emissions, the constitutional authority of national and/or provincial/state governments to impose emissions taxes, regulate emissions and/or regulate efficiency standards. It is also important to consider potential conflicts between carbon reduction policies and policies with other objectives, such as keeping energy costs to consumers as low as possible.

Practically every policy (except cost-saving energy conservation options)[20], no matter what instrument is used to implement it, has a cost in terms of utilization of resources and ensuing price increases that leads to reductions in output, income, employment, or other measures of economic well-being. The total cost is usually higher than the direct cost due to interactions with other segments of the economy and with existing policies ("general equilibrium" effects). Regardless of where the compliance obligation is imposed, the cost ultimately is borne by the general public as consumers, shareholders, employees, taxpayers, and recipients of government services[21]. The cost can have competitiveness impacts if some emitters in other jurisdictions are not subject to similar policies. But societal benefits, such as improved public health and reduced environmental damage, may offset part or all of the cost of implementing the policy.

To achieve a given emission reduction target, regulations that require each affected source to meet a specified emissions limit or implement specified controls are almost always more costly than emissions trading or emissions taxes because they require each affected source to meet the regulation regardless of cost rather than allowing emission reductions to be implemented where the cost is lowest (Bohm and Russell, 1986)[22]. The cost saving available through trading or an emissions tax generally increases with the diversity of sources and share of total emissions covered by the policy (Rose and Oladosu, 2002)[23]. A policy that raises revenue (an emissions tax or auctioned allowances) has a lower cost to the economy than a policy that does not, if the revenue is used to reduce existing distortionary taxes[24] such as sales or income taxes (see, *e.g.*, Parry *et al.*, 1999).

4.5.3 Source Reduction Policies

Historically CO_2 emissions have not been regulated directly. Some energy-related CO_2 emissions have been regulated indirectly through energy policies, such as promotion of renewable energy, and efficiency standards and ratings for equipment, vehicles, and some buildings. Methane emissions from oil and gas production, underground coal mines, and landfills have been regulated, usually for safety reasons.

Policies with other objectives can have a significant impact on CO_2 emissions. Policies to encourage production or use of fossil fuels, such as favorable tax treatment for fossil fuel production, increase CO_2 emissions. Similarly, urban plans and infrastructure that facilitate automobile use rather than public transit increase CO_2 emissions. In contrast, a tax on vehicle fuels reduces CO_2 emissions[25].

Carbon dioxide emissions are suited to emissions trading and emissions taxes. These policies allow considerable flexibility in the location and, to a lesser extent, the timing of the emission reductions[26]. The environmental impacts of

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[20] These are often called "no regret" options.

[21] The source with the compliance obligation passes on the cost through some combination of higher prices for its products, negotiating lower prices with suppliers, layoffs, and/or lower wages for employees, and lower profits that lead to lower tax payments and lower share prices. Other firms that buy the products or supply the inputs make similar adjustments. Governments raise taxes or reduce services to compensate for the loss of tax revenue. Ultimately, all of the costs are borne by the general public.

[22] As well, regulation is generally inferior to emissions trading or taxes in inducing technological change.

[23] These policies encourage implementation of the lowest cost emission reductions available to the affected sources. They establish a price (the emissions tax or the market price for an allowance) for a unit of emissions and then allow affected sources to respond to the price signal. In principle, these two instruments are equivalent in terms of achievement of the efficient allocation of resources, but they may differ in terms of equity because of how the emission permits are initially distributed and whether a tax or subsidy is used. It is easier to coordinate emissions trading programs than emissions taxes across jurisdictions.

[24] A distortionary tax is one that changes the relative prices of goods or services. For example, income taxes change the relative returns from work, leisure, and savings.

[25] Initially the reduction may be small because demand for gasoline is not very sensitive to price, but over time the tax causes people to adjust their travel patterns and the vehicles they drive, thus yielding larger reductions.

[26] An emissions trading program may allow participants to buy credits issued to entities not covered by the program for emission reductions or increased carbon sequestration. Determination of

CO_2 depend on its atmospheric concentration, which is not sensitive to the location or timing of the emissions. Apart from ground-level safety concerns, the same is true of CH_4 emissions. In addition, the large number and diverse nature of the CO_2 and CH_4 sources means that use of such policies can yield significant cost savings but may also be difficult to implement.

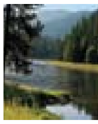
Regulations setting maximum emissions on individual sources or efficiency standards for appliances and equipment might be preferred to emissions trading and taxes. Such regulations may be desirable where monitoring actual emissions is costly or where firms or individuals do not respond well to price signals due to lack of information or market imperfections. Energy efficiency standards for appliances, buildings, equipment, and vehicles tend to fall into this category (OECD, 2003a)[27]. In some cases, such as refrigerators, standards have been used successfully to drive technology development.

4.5.4 Terrestrial Sequestration Policies

To date, policies that explicitly encourage carbon sequestration in terrestrial systems have taken the form of modifying conservation programs aimed at other environmental objectives to include rewards for increasing carbon uptake by forests and agricultural soils. For example, the United States Department of Agriculture modified the enrollment criteria of the Conservation Reserve Program (CRP) and the Environmental Quality Incentives Program to give additional consideration to bids offering to install specific practices and technologies that sequester more carbon. The CRP also was modified to give landowners the right to sell carbon sequestered on lands enrolled in the program in private carbon markets. Policies that affect crop choice (support payments, crop insurance, disaster relief) and farmland preservation (conservation easements, use value taxation, agricultural zoning) may increase or reduce the carbon stock of agricultural soils. And policies that encourage higher agricultural output (support payments) can reduce the carbon stored by agricultural soils if they lead to increased tillage; such policies may increase stored carbon or be neutral with respect to carbon if they do not increase tillage.

A broad suite of policies are potentially available to increase terrestrial carbon stocks:

- Regulations, such as: requirements to limit or offset carbon emissions from land-use practices, requirements to reforest areas that have been logged, good practice standards, and requirements to establish carbon reserves.
- Market-based approaches, including: product labeling, tradable development rights, markets for terrestrial carbon[28,29], and taxes on carbon emission from terrestrial systems.
- Incentives: tax credits for good management practices, cost-sharing of practice costs, payment of land rents for set-asides, outcome oriented payments based on carbon stored or sequestered (Feng *et al*., 2003).
- Education and extension: Training, technical assistance, guidance on best management practices, education on impacts of alternative management practices, recommendations, technology pilots, and efforts to address lack of experience, learning costs, and risk aversion (Sedjo, 2001; Sedjo and Swallow, 2002).



Policies to enhance terrestrial carbon sinks have significant potential to store additional carbon more cost effectively than emissions reductions in other sectors, at least for the next few decades (EPA, 2005). The amount of carbon that could be sequestered and the cost-effectiveness of this option would depend on the policies employed and the value placed on terrestrial carbon. (*e.g.*, Marland *et al*., 2001).

4.5.5 Research and Development Policies

Policies to stimulate research and development of lower emissions technologies can reduce the cost of meeting a long-term reduction target. Policies to reduce CO_2 emissions also influence the rate and direction of technological change (OECD, 2003a; Stern, 2006). By stimulating additional technological change, such policies can reduce the cost of meeting a given reduction target (Goulder, 2004; Grubb *et al*., 2006; Stern, 2006). Such induced technological change tends to justify earlier and more stringent emission reduction targets (Goulder, 2004; Grubb *et al*., 2006).

The environmental impacts of CO_2 depend on its atmospheric concentration, which is not sensitive to the location or timing of the emissions.

Two types of policies are needed to ensure that available technologies can achieve a given cumulative CO_2 reduction or concentration target at least cost. Direct support for research and development produces less emission-intensive technologies and policies to reduce emissions and increase sequestration create a market for those technologies. The combination of "research push" and "market pull" policies is more effective than either strategy on its own (Goulder, 2004; CBO, 2006; Stern, 2006). Policies should encourage research and development for all promising technologies

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the quantity of credits earned requires resolution of many issues, including the baseline, leakage, and additionality.

[27] The efficiency of standards sometimes can be improved by allowing manufacturers that exceed the standard to earn credits that can be sold to manufacturers that do not meet the standard.

[28] There needs to be a buyer for the credits, such as sources subject to CO_2 emissions trading program or an offset requirement.

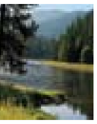
[29] Since carbon sequestered in terrestrial plants and soils can be released from these sinks (*e.g.*, through forest fires or a return to tillage), markets for terrestrial carbon may need to address the permanence of the carbon sequestered. A number of options are available to address permanence.

because there is considerable uncertainty about which ones will ultimately prove most useful, socially acceptable, and cost-effective[30].

4.6 CONCLUSIONS

Actions to reduce projected CO_2 and CH_4 concentrations in the atmosphere should recognize the following:

- Emissions are produced by millions of diverse sources, most of which (*e.g.*, power plants, factories, building heating and cooling systems, and large appliances) have lifetimes of 5 to 50 years, and so are likely to adjust only slowly at reasonable cost.
- Potential uptake by agricultural soils and forests is significant but small to moderate relative to emissions (Chapter 11 this report) and can be reversed at any given location by natural phenomena or human activities. Policies to enhance and maintain terrestrial carbon sinks have significant potential to store additional carbon more cost-effectively than emissions reductions in other sectors, at least for the next few decades.
- Technological change will have a significant impact on the cost because emission reductions will be implemented over a long time, and new technologies should lower the cost of future reductions.
- Many policies implemented by national, state/provincial, and municipal jurisdictions and private firms to achieve objectives other than carbon management increase or reduce CO_2/CH_4 emissions.



Under a wide range of assumptions, policies to reduce atmospheric CO_2 and CH_4 concentrations cost-effectively in the short and long term would:

- Encourage adoption of low cost emission reduction and sink enhancement actions. An emission trading program or emissions tax that covers as many sources and sinks as possible, combined with regulations where appropriate, is an example of a way to achieve this. Use of revenues from auctioned allowances and/or emission taxes could reduce the net economic cost of emission reduction policies.
- Stimulate development of technologies that lower the cost of emissions reduction, carbon capture and sequestration, and sink enhancement.
- Adopt appropriate regulations for sources or actions subject to market imperfections, such as energy efficiency measures and cogeneration.
- Revise existing policies at the national, state/provincial, and local level related to objectives other than carbon management so that the objectives, if still relevant, are achieved with lower CO_2 or CH_4 emissions.

Implementation of such policies at a national level, and cooperation at an international level, would reduce the overall cost of achieving a carbon reduction target by providing access to more low-cost mitigation/sequestration options.

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[30] In other words, research and development is required for a portfolio of technologies. Because technologies have global markets, international cooperation to stimulate the research and development, as occurs through the International Energy Agency and the Asia-Pacific Partnership on Clean Development and Climate (APP), is appropriate.

CHAPTER 5

How Can We Improve the Usefulness of Carbon Science for Decision Making?

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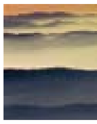


KEY FINDINGS

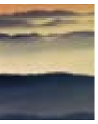
- Decision makers are seeking more comprehensive information on the carbon cycle and on carbon management options across scales and sectors. Carbon management is a relatively new concept not only for decision makers and members of the public, but also for the science community.
- Improving the usefulness of carbon science in North America will require stronger commitments to generating high quality science that is also decision-relevant.
- Research on the production of policy-relevant scientific information suggests several ways to improve the usefulness of carbon science for decision making, including co-production of knowledge, development of applied modeling tools for decision support, and use of "boundary organizations" that can help carbon scientists and decision makers communicate and collaborate.
- A number of initiatives to improve understanding of decision support needs and options related to the carbon cycle are under way, some as a part of the Climate Change Science Program (CCSP).
- Additional pilot projects should be considered aimed at enhancing interactions between climate change scientists and parties involved in carbon management activities and decisions.

5.1 INTRODUCTION: THE CHALLENGE OF "USABLE" CARBON SCIENCE

This chapter answers two questions:

- How well is the carbon cycle science community doing in "decision support" of carbon cycle management, *i.e.*, in responding to decision makers' demands for carbon cycle management information?
- How can the carbon cycle science community improve such decision support?

Chapters in Parts 2 and 3 of this report identify many research priorities, including assessing the potential for geological storage of carbon dioxide (CO_2), quantifying expansion of the North American carbon sink, and identifying the economic impact of carbon tax systems. This chapter focuses on improving communication and collaboration between scientific researchers and carbon managers, to help researchers be more responsive to decision making, and carbon managers be better informed in making policy, investment, and advocacy decisions.



Humans have been inadvertently altering the Earth's carbon cycle since the dawn of agriculture, and more rapidly since the industrial revolution. These influences have become large enough to cause significant climate change (IPCC, 2007). In response, environmental advocates, business executives, and policy-makers have increasingly recognized the need to manage the carbon cycle deliberately. Effective carbon management requires that the variety of people whose decisions affect carbon emissions and sinks have relevant, appropriate science. Yet, carbon cycle science is rarely organized or conducted to support decision making on managing carbon emissions, uptake and storage (sequestration), and impacts. This reflects that, until recently, scientists have approached carbon cycle science as basic science and only a relatively small, although growing, portion of non-scientist decision makers have demanded carbon cycle information. Consequently, emerging efforts to manage carbon are less informed by carbon cycle science than they could be (Dilling *et al.*, 2003). Applying carbon science to carbon management requires making carbon cycle science more useful to public and private decision-makers at all levels, from national and international policymakers to the executives and employees of corporations to the millions of individuals whose myriad consumer and household decisions are central to human impacts on the carbon cycle. In particular, scientists and decision makers will need to identify the information most needed in specific sectors for carbon management, adjust research priorities, and develop mechanisms that enhance the credibility of the information generated and the responsiveness of the information-generating process to address stakeholder's views (Lahsen and Nobre, 2007; Mitchell *et al.*, 2006; Cash *et al.*, 2003). Combining some "applied" or "solutions-oriented" research with a portfolio that also includes basic science would make carbon science more directly relevant to decision making.

Humans have been inadvertently altering the Earth's carbon cycle since the dawn of agriculture, and more rapidly since the industrial revolution. These influences have become large enough to cause significant climate change.

5.2 TAKING STOCK: WHERE ARE WE NOW IN PROVIDING DECISION SUPPORT TO IMPROVE CAPACITIES FOR CARBON MANAGEMENT?

How effective is the scientific community at providing decision support for carbon management? The Climate Change Science Program (CCSP) Strategic Plan defines decision support as: "the set of analyses and assessments, interdisciplinary research, analytical methods, model and data product development, communication, and operational services that provide timely and useful information to address questions confronting policymakers, resource managers, and other stakeholders" (U.S. Climate Change Science Program, 2003).

Who are the potential stakeholders for information related to the carbon cycle and what are the options and measures for altering human influences on that cycle? Most people constantly, but unconsciously, make decisions that affect the carbon cycle through their use of energy, transportation, living spaces, and natural resources. Increasing attention to climate change has led some policy makers, businesses, advocacy groups, and consumers to begin making choices that consciously limit carbon emissions[1]. Whether carbon emission reductions are driven by political pressures or legal requirements, by economic opportunities, or consumer pressures, or by moral or ethical commitments to averting climate change, people and organizations are seeking information that can help them achieve their specific carbon-related or climate-related goals[2]. Even in countries and economic sectors that lack a consensus on the need to manage carbon, some people and organizations have begun to experiment with carbon-limiting practices and investments in anticipation of a carbon-constrained future.

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[1] For examples, see Box 5.1

[2] For example, carbon science was presented at recent meetings of the West Coast Governors' Global Warming Initiative and the Climate Action Registry [http://www.climateregistry.org/EVENTS/PastConferences/; http://www.climatechange.ca.gov/events/2005_conference/presentations/]

In designing and producing this report, we engaged individuals from a wide range of sectors and activities, including forestry, agriculture, utilities, fuel companies, carbon brokers, transportation, non-profits, and local and federal governments. Although we did not conduct new research on the informational or decision support needs of stakeholders, a preliminary review suggests that many stakeholders may be interested in carbon-related information (see Box 5.1).

5.3 CURRENT APPROACHES AND TRENDS

Interest in, and attention paid to, carbon information has increased incrementally over the last 20 years. Future levels of interest are likely to depend on perceived risks from carbon emissions as well as on whether and how mandatory and incentive-based policies related to carbon management evolve. As efforts at deliberate carbon management become increasingly common, decision makers from the local to the national level are increasingly open to or actively seeking carbon science information as a direct input to policy and investment decisions (Apps *et al*., 2003). The government of Canada, having ratified the Kyoto Protocol, has been exploring emission reduction opportunities and offsets and has identified specific needs for applied research (Environment Canada, 2005). For example, Canada's national government recently entered a research partnership with the province of Alberta to assess geological sequestration of CO_2, to develop fuel cell technologies using hydrogen, and to expand the use of vegetative matter (biomass) and biowaste for energy production (Western Economic Diversification Canada, 2006).

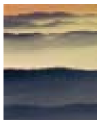
Some stakeholders in the United States are actively using carbon science to move forward with voluntary emissions offset programs. For example, the Chicago Climate Exchange brokers agricultural carbon credits in partnership with the Iowa Farm Bureau[3]. Many cities and several states have established commitments to manage carbon emissions, including regional partnerships on the east and west coasts, and non-governmental organizations and utilities have begun to experiment with pilot sequestration projects (Box 5.1). In Europe, for example, mandatory carbon emissions policies have resulted in intense interest in carbon science by those directly affected by such policies (Schröter *et al*., 2005).

In the United States, federal carbon science has very few mechanisms to assess demand for carbon information across scales and sectors. Thus far, federally-funded carbon science has focused on basic research to clarify fundamental uncertainties in the global carbon cycle and local and regional processes affecting the exchange of carbon (Dilling, in press). Most federal efforts are organized under the CCSP. The National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF) manage almost two-thirds of this effort and their missions are limited to basic research, not decision support (CCSP, 2006; Dilling, 2007). Research efforts have also been undertaken at the Department of Energy (DOE), the Department of Agriculture (USDA)[4], and the Department of Interior's Geological Survey (USGS/DOI). Significant technology efforts are underway in the Climate Change Technology Program (CCTP), a sister program to the CCSP focused on technology development. Increasing linkages among these programs may increase the usefulness of CCSP carbon-related research to decision makers. For over a decade, the National Oceanic and Atmospheric Administration (NOAA) Climate Program Office has invested in research and institutions intended to improve the usability of climate science, although that investment is small relative to the investment in climate science itself and has focused on the usability of climate, rather than carbon cycle, science.

As efforts at deliberate carbon management become increasingly common, decision makers from the local to the national level are increasingly open to or actively seeking carbon science information as a direct input to policy and investment decisions.

Until recently, the concept of "carbon management" has not been widely recognized—even now, most members of the public do not understand the term "carbon sequestration" or its potential implications (Shackley *et al*., 2005; Curry *et al*., 2004). However, the carbon cycle science community is beginning to recognize that it may have information relevant to policy and decision making. Thus prominent carbon scientists have called for "coordinated rigorous, interdisciplinary research that is strategically prioritized to address societal needs" (Sarmiento and Wofsy, 1999) and the North American Carbon Program's (NACP) "Implementation Plan" lists decision support as one of four organizing questions (Denning *et al*., 2005).

That same plan, however, states that the scientific community knows relatively little about the likely users of information that the NACP will produce. Indeed, the National Academy of Sciences' review of the CCSP stated that "as the decision support elements of the program are implemented, the CCSP will need to do a better job of identifying stakeholders and the types of decisions they need to make" (NRC, 2004). Moreover, they state that "managing risks



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[3] http://www.iowafarmbureau.com/special/carbon/default.aspx

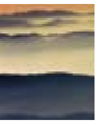
[4] For example, the Consortium for Agricultural Soil Mitigation of Greenhouse Gases (CASMGS) was recently funded by the USDA to provide information and technology necessary to develop, analyze, and implement carbon sequestration strategies.

BOX 5.1: Sectors and Stakeholders Expressing Interest and/or Participating in the SAP 2.2 Process

This list of sectors is neither exhaustive nor is it based on a systematically rigorous assessment, but is meant to demonstrate the wide variety of stakeholders with a potential interest in carbon-related information.

Agriculture: Tillage and other farming practices significantly influence carbon storage in agricultural soils. Managing these practices presents opportunities both to slow carbon loss and to restore carbon in soils. Farmers have been quite interested in carbon management as a means to stimulate rural economic activity. Since much of the agricultural land in the United States is privately owned, both economic forces and governmental policies will be critical factors in the participation of this sector in carbon management. (Chapter 10 this report).

Forestry: Forests accumulate carbon in above-ground biomass as well as soils. The carbon impact of planting, conserving, and managing forests has been an area of intense interest in international negotiations on climate change (IPCC, 2000). Whether seeking to take advantage of international carbon credits, to offset other emissions, or to simply identify environmental co-benefits of forest actions taken for other reasons, governments, corporations, landowners, and conservation groups may need more information on and insight into the carbon implications of forestry decisions ranging from species selection to silviculture, harvesting methods, and the uses of harvested wood. (Chapter 11 this report).



Utilities and Industries: In the United States, over 85% of energy produced comes from fossil fuels with relatively high carbon intensity. The capital investment and fuel source decisions of utilities and energy-intensive industries thus have major carbon impacts. A small but growing number of companies have made public commitments to reducing carbon emissions, developed business models that demonstrate sensitivity to climate change, and begun exploring carbon capture and storage opportunities. For example, Cinergy, a large Midwestern utility, has experimented with carbon-offset programs in partnership with The Nature Conservancy. (Chapter 6 and 8 this report).

Transportation: Transportation accounts for approximately 37% of carbon emissions in the United States, and about 22% worldwide. Governmental infrastructure investments, automobile manufacturers' decisions about materials, technologies and fuels, and individual choices regarding auto purchases, travel modes, and distances all have significant impacts on carbon emissions. (Chapter 7 this report).

Government: In the United States, national policies currently rely primarily on voluntary measures and incentive structures (U.S. Department of State, 2004; Richards, 2004). Canada, having ratified the Kyoto Protocol, has direct and relatively immediate needs for information that can help it meet its binding targets as cost-effectively as possible (Environment Canada, 2005). The Mexican government appears to be particularly interested in locally relevant research on natural and human influences on the carbon cycle, likely impacts across various regions, and the costs, benefits, and viability of various management options (Martinez and Fernandez-Bremauntz, 2004). Below the national level, more and more states and local governments are taking steps, including setting mandatory policies, to reduce carbon emissions, and may need new carbon cycle science scaled to the state and local level to manage effectively. For example, nine New England and mid-Atlantic states have formed a regional partnership, also observed by Eastern Canadian provinces, to reduce carbon emissions through a cap and trade program combined with a market-based emissions trading system (Regional Greenhouse Gas Initiative—RGGI—www.rggi.org). (Chapters 4 and 14 this report).

Non-Profits and Non-Governmental Organizations (NGOs): Many environmental and business-oriented organizations have an interest in carbon management decision making. Such organizations rely on science to support their positions and to undercut the arguments of opposing advocates. There has been substantial criticism of "advocacy science" in the science-for-policy literature, and new strategies will need to be developed to promote constructive use of carbon cycle science by advocates (Ehrmann and Stinson, 1999; Adler *et al.*, 1999).

and opportunities requires stakeholder support on a range of scales and across multiple sectors, which in turn implies an understanding of the decision context for stakeholders" (NRC, 2004). Successful decision support (*i.e.*, science that improves societal outcomes) requires understanding of who the users are and of the kind of information they are likely to deem relevant and bring to bear on their decision making. Without such knowledge, information runs the risk of being "left on the loading-dock" and not used (Cash et al., 2006; Lahsen and Nobre, 2007).

Some programs within CCSP may shed light on how to link carbon science to user needs. NASA has an Applied Sciences program that seeks to find uses for its data and modeling products using "benchmarking systems," and the USDA and DOE have invested significant resources in science that might inform carbon sequestration efforts and carbon accounting in agriculture and forests. However, these programs have not been integrated into a broader framework self-consciously aimed at making carbon cycle science more useful to decision makers.

Funding agencies, scientists, policy makers, and private sector managers can improve the usefulness of carbon science programs in North America by increasing their commitments to generating decision-relevant carbon cycle information and by integrating those programs more fully into forums and institutions involved in carbon cycle management. The participatory methods and boundary spanning institutions identified in the next section help both refine research agendas and accelerate the application of research results to carbon management and societal decision making.

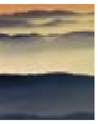
5.4 OPTIONS FOR IMPROVING THE APPLICABILITY OF SCIENTIFIC INFORMATION TO CARBON MANAGEMENT AND DECISION MAKING

Studies of the creation and use of knowledge for decision making have found that information must be perceived not only as credible, but also as relevant to high priority decisions and as stemming from a process that decision makers view as responsive to their concerns (Mitchell *et al.*, 2006; Cash *et al.*, 2003). Even technically and intellectually rigorous science lacks influence with decision makers if decision makers perceive it as not addressing the decisions they face, as being biased, or as having ignored their views and interests.

Research on the production of policy-relevant scientific information suggests several strategies that can maintain the integrity of the research endeavor while increasing its policy relevance. Although communicating results more effectively is clearly important, generating science that is more applicable to decision making may require deeper changes in the way scientific information is produced. Carbon cycle scientists and carbon decision makers will need to develop methods for interaction that work best in the specific arenas in which they work. At their core, strategies will be effective to the extent that they promote interaction among scientists and stakeholders in the development of research questions, selection of research methods, and review, interpretation, and dissemination of results (Adler *et al.*, 1999; Ehrmann and Stinson, 1999; NRC, 1999; NRC, 2005; Farrell and Jaeger, 2005; Mitchell *et al.*, 2006). Such processes work best when they enhance the usability of the research while preserving the credibility of both scientists and stakeholders. Transparency and expanded participation are important for guarding against politicization and enhancing usability.

Examples of joint scientist-stakeholder development of policy relevant scientific information include:

- *Co-production of research knowledge (e.g., Regional Integrated Sciences and Assessments)*: In regional partnerships across the United States, university researchers work closely with local operational agencies and others that might incorporate climate information in decision making. New research is developed through ongoing, iterative consultations with all partners (Lemos and Morehouse, 2005). Co-production of research knowledge involves efforts to reach out to, educate, and involve stakeholders in programs that facilitate a dialog



of researchers and stakeholders consulting with and engaging each other in identifying near-term research questions and longer-term research trajectories.

- *Institutional experimentation and adaptive behavior* (*e.g., adaptive management)*: Adaptive management acknowledges our inherent uncertainty about how natural systems respond to human management, and periodically assesses the outcomes of management decisions and adjusts those decisions accordingly, a form of deliberate "learning by doing" (*cf.*, Holling, 1978). Adaptive management principles have been applied to several resources where multiple stakeholders are involved, including management of river systems and forests (Holling, 1995; Pulwarty and Redmond, 1997; Mitchell *et al.*, 2004; Lemos and Morehouse, 2005).
- *Assessments as policy components* (*e.g., recovering the stratospheric ozone layer)*: Assessments that were credible, relevant, and responsive played a significant role in the Montreal Protocol's success in phasing out the use of ozone-depleting substances. A highly credible scientific and technical assessment process with diverse academic and industry participation is considered crucial in the Protocol's success (Parson, 2003).
- *Mediated modeling*: Shared tools can facilitate scientist-user interactions, help diverse groups develop common knowledge and understanding of a problem, and clarify common assumptions and differences. In mediated modeling, participants from a wide variety of perspectives jointly construct a computer model to solve complex environmental problems or envision a shared future. The process has been used for watershed management, endangered species management, and other difficult environmental issues (Van den Belt, 2004).
- *Carbon modeling tools as decision support*: Although the United States government has not yet adopted a carbon management policy, some federal agencies have begun to develop online decision support tools, with customizable user interfaces, to estimate carbon sequestration in various ecosystems and under various land-use scenarios (see the NASA Ames Carbon Query and Evaluation Support Tools, http://geo.arc.nasa.gov/sge/casa/cquestwebsite/index.html; the U.S. Forest Service Carbon Online Estimator, http://ncasi.uml.edu/COLE/;and Colorado State's CarbOn Management Evaluation Tool, http://www.cometvr.colostate.edu/).

Over time, well-structured scientist-stakeholder interaction can help both scientists and decision makers (Moser, 2005). Scientists learn to identify research questions that are both scientifically interesting and relevant to decisions, and to present their answers in ways that audiences are more likely to find compelling. Non-scientists learn what questions science can and cannot answer. Such interactions clarify the boundary between empirical questions that scientists can answer (*e.g.*, the sequestration potential of a particular technology) and issues that require political resolution (*e.g.*, the appropriate allocation of carbon reduction targets across firms). Institutional arrangements can convert *ad hoc* successes in scientist-stakeholder interaction into systematic and ongoing networks of scientists, stakeholders, and managers. Such "co-production of knowledge," can enhance both the scientific basis of policy and management and the research agenda for applied science (Lemos and Morehouse, 2005; Gibbons *et al*., 1994; Patt *et al*., 2005a).

That said, such interactive approaches have limitations, risks, and costs. Scientists may be reluctant to involve non-scientists who "should" be interested in a given issue, but who can add little scientific value to the research, and whose involvement requires time and effort. Involving private sector firms may require scientists accustomed to working in an open informational environment to navigate in a world of proprietary information. Scientists may also avoid applied, participatory research if they do not see it producing the "cutting edge" (and career enhancing) science most valued by other scientists (Lahsen and Nobre, 2007; Lemos and Morehouse, 2005). Public and private carbon cycle science programs, as well as universities and research institutes, more generally, can help address these obstacles by recognizing that they exist and altering incentive structures to reward innovation in applied research through endowed chairs, fellowships, research grants, and the like.

Some stakeholders may lack the financial resources, expertise, time, or other capacities necessary to meaningful participation. Some will distrust scientists in general, and government-sponsored science in particular, for cultural, institutional, historical, or other reasons. Some may reject the idea of interacting with those with whom they disagree politically or compete economically. Stakeholders may try to manipulate research questions and findings to serve their political or economic interests. In addition, stakeholders often show little interest in diverting their time from other activities to what they perceive as the slow and too-often fruitless pursuit of scientific knowledge (Patt *et al.*, 2005b).

Where direct stakeholder participation proves too difficult, costly, unmanageable, or unproductive, scientists and research managers need other methods to identify the needs of potential users. Science on the one hand, and policy, management, and decision making on the other, often exist as separate social and professional realms, with different traditions, norms, codes of behavior, and reward systems. The boundaries between such realms serve many useful functions but can inhibit the transfer of useful knowledge across those boundaries. A boundary organization is an institution that "straddles the shifting divide" between politics and science (Guston, 2001). Boundary organizations are accountable to both sides of the boundary and involve professionals from each. Boundary spanning individuals and organizations may facilitate the uptake of science by translating scientific findings so that stakeholders find them more useful and by stimulating adjustments in research agendas and approach.

Boundary organizations can exist at a variety of scales and for a variety of purposes. For example, cooperative agricultural extension services and non-governmental organizations (NGOs) successfully convert large-scale scientific understandings of weather, aquifers, or pesticides into locally-tuned guidance to farmers (Cash, 2001). The International Research Institute for Climate Prediction focuses on seasonal-to-interannual scale climate research and modeling to make their research results useful to farmers, anglers, and public health officials (*e.g.*, Agrawala *et al.*, 2001). The Subsidiary Body for Scientific and Technological Advice of the United Nations Framework Convention on Climate Change serves as an international boundary organization that links information and assessments from expert sources (such as the Intergovernmental Panel on Climate Change [IPCC]) to the Conference of the Parties, which focuses on setting policy[5]. The University of California Berkeley Digital Library Project *Calflora* has explicitly designed their database on plants to support environmental planning (Van House *et al.*, 2003).

Though attractive in principle, boundary organizations may not be effective in practice. They may fail to be useful if they are not responsive to both the stakeholders and scientists they seek to engage. They may be captured by one particular stakeholder or science interest. Their usefulness may decline over time if they are unable to keep pace with the salient issues of the principals on either side of the boundary.

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Even where boundary organizations do facilitate the translation of scientific expertise for policy, other significant challenges exist in the use of knowledge. People fail to integrate new research and information in their decisions for many reasons. People often are not motivated to use information that supports policies they dislike or that conflicts with pre-existing preferences, interests, or beliefs, or with cognitive, organizational, sociological, or cultural norms (*e.g.*, Douglas and Wildavsky, 1984; Lahsen, 1999; Yaniv, 2004; Lahsen, 2007). These tendencies are important components of a healthy democratic process. Developing processes to make carbon science more useful to decision makers will not guarantee its use, but will make its use more likely.

5.5 RESEARCH NEEDS TO ENHANCE DECISION SUPPORT FOR CARBON MANAGEMENT

The demand for detailed analysis of carbon management issues and options across major economic sectors, nations, and levels of government in North America is likely to grow substantially in the near future. This will be especially true in jurisdictions that place policy constraints on carbon budgets, such as Canada, United States' states comprising the Regional Greenhouse Gas Initiative, or the U.S. State of California. Although new efforts are underway in some federal agencies, carbon cycle science in the United States could be organized and carried out to better and more systematically meet this potential demand. Effective implementation of the goals of the Climate Change Science Program "requires focused research to develop decision support resources and methods" (NRC, 2004). Relevant science could evaluate the impacts, technical feasibility, and economic potential of the wide range of existing and newly-developed options that are likely to be proposed in response to growing regional and national interest in carbon management.

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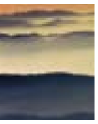
[5] http://unfccc.int/2860.php

Creating information for decision support should differ significantly from doing basic science. In such "use-inspired research," societal need is as important as scientific curiosity (Stokes, 1997). Scientists and carbon managers need to improve their joint understanding of the top priority questions facing carbon-related decision making. They need to collaborate more effectively in undertaking research and interpreting results in order to answer those questions.

A first step might involve developing a formal process "for gathering requirements and understanding the problems for which research can inform decision makers outside the scientific community," including forming a decision support working group (Denning *et al*., 2005). The NRC has recommended that the CCSP's decision support components could be improved by organizing various deliberative activities, including workshops, focus groups, working panels, and citizen advisory groups to: "1) expand the range of decision support options being developed by the program; 2) to match decision support approaches to the decisions, decision makers, and user needs; and 3) to capitalize on the practical knowledge of practitioners, managers, and laypersons" (NRC, 2004).



5.6 SUMMARY AND CONCLUSIONS

The carbon cycle is influenced through both deliberate and inadvertent decisions by diverse and spatially dispersed people and organizations, working in many different sectors and at different scales. To make carbon cycle science more useful to decision makers, we suggest that leaders in the scientific and program level carbon science community initiate the following steps:

- Identify categories of decision makers for whom carbon cycle science is a relevant concern, focusing on policy makers and private sector managers in carbon-intensive sectors (energy, transport, manufacturing, agriculture, and forestry).
- Evaluate existing information about carbon impacts of actions in these arenas, and assess the need and demand for additional information. In some cases, demand may need to be fostered through an interactive process.
- Encourage scientists and research programs to experiment with incremental, as well as major, departures from existing practice with the goal of making carbon cycle science more credible, relevant, and responsive to carbon managers.
- Involve experts in the social sciences and communication as well as experts in physical, biological, and other natural science disciplines in efforts to produce usable science.
- Consider initiating participatory pilot research projects and identifying existing boundary organizations (or establishing new ones) to bridge carbon management and carbon science.