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

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WHY A REPORT ON THE CARBON CYCLE?

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

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

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

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

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

The Carbon Cycle and Climate Change

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

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

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

Other Implications of an Imbalance in the Carbon Budget

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

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

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

Why the Carbon Budget of North America?

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

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

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

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

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

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

CARBON CYCLE SCIENCE IN SUPPORT OF CARBON MANAGMENT DECISIONS

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

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

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

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The Global Carbon Cycle

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

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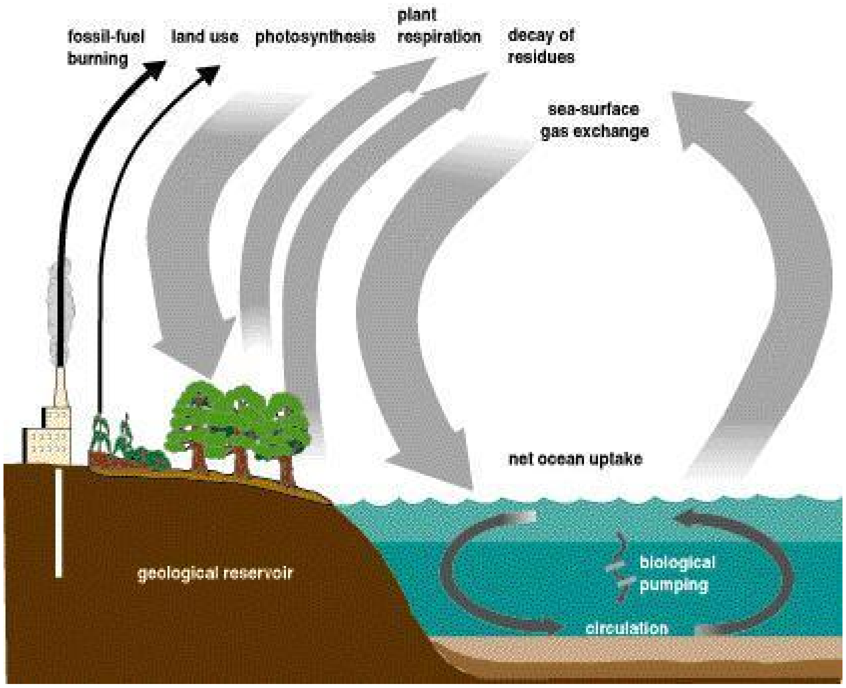

Figure 1-1. The global carbon cycle. Carbon cycles through pools or reservoirs of carbon on land, in the ocean, and in sedimentary rock formations over daily, seasonal, annual, millennial and geological time scales. See the accompanying text box.

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 CO_2 concentrations have risen by 31% since 1850, and they are now higher than they have been for 420,000 years.
- North America is responsible for approximately 27% of the emissions produced globally by fossil-fuel combustion, with the United States accounting for 86% of the North American total.
- Anthropogenic emissions (a carbon source) dominate the carbon budget of North America. Largely unmanaged, unintentional processes lead to a smaller carbon sink (uptake of carbon). The sink is approximately 30% of the North American emissions, 9% of global emissions, and approximately 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.

THE GLOBAL 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) (Fig. 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 (Fig. 2-2), changing the radiation balance of the Earth (Hansen *et al*., 2005), and most likely warming the planet (Mitchell *et al*., 2001). 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. The background or unmanaged parts of the carbon cycle have, in fact, changed dramatically over the past two centuries. The consequence of these changes is that only about 40% ± 15% of the carbon dioxide emitted to the atmosphere from fossil-fuel combustion and forest clearing has remained there (with most of the uncertainty in this number due to the uncertainty in carbon lost from forest clearing) (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 Gt of carbon. [Throughout this chapter, we will present the pools and fluxes in the carbon cycle 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 2-1. 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), and the details of the land cycle. For all panels, carbon stocks are in brackets, and fluxes have no brackets. Pre-anthropogenic stocks and fluxes are in black. Anthropogenic perturbations are in red. For stocks, the anthropogenic perturbations are the cumulative total since 1850. Anthropogenic fluxes are means for the 1990s. Redrawn from (Sabine *et al.*, 2004b) with updates as discussed in the text.

Figure 2-2. Atmospheric CO_2 concentration from 1850 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 carbon dioxide 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).

The Unmanaged Global Carbon Cycle

The modern background, or unmanaged, carbon cycle includes the processes that occur in the absence of human actions. These processes are, however, 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) (Fig. 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 biomass 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 yr^{-1} moves from the oceans to the atmosphere (While the gross fluxes have a substantial uncertainty, the difference is known to within ± 0.3 Gt) . These air-sea fluxes are driven by internal cycling within the oceans that governs exchanges between pools of dissolved CO_2, bicarbonate (HCO_3^-), and carbonate ($CO_3^=$); organic matter; and calcium carbonate.

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 0.55 ± 0.15 Gt C yr^{-1} transferred to the oceans by rivers and released from the oceans to the atmosphere. As a consequence, the level of carbon dioxide in the atmosphere varied by less than 25 ppm in the 10,000 years prior to 1850 (Joos and Prentice, 2004). But atmospheric CO_2 was not always so stable. During the preceding 420,000 years, atmospheric CO_2 was 180–200 ppm during ice ages and approximately 275 ppm during interglacials (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).

In the distant past, the global carbon cycle was out of balance in a different way. Fossil fuels are the product of prehistorically sequestered 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). It also led to a near doubling of atmospheric oxygen (Falkowski *et al.*, 2005).

Anthropogenic Perturbations

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 manufacture from 1751 through 2003 are 304 ± 30 Gt (Marland and Rotty, 1984; Andres *et al*., 1999) (with updates through 2003 online at http://cdiac.ornl.gov/trends/emis/tre_glob.htm). Land use change from 1850 to 2003, mostly from the clearing of forests, added another 162 ± 160 Gt (DeFries *et al*., 1999; Houghton, 1999a)(with updates through 2000 online at http://cdiac.ornl.gov/trends/landuse/houghton/houghton.html. We extrapolated the total through 2003 based on the assumption that the fluxes in 2001-2003 were the same as that in 2000.) . 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-nineteenth century, with atmospheric CO_2 rising by 31% (i.e., from 287 ppm to 375 ppm in 2003; the increase from the mid-eighteenth century was 35%).

In 2003 the three major countries of North America (Canada, Mexico, and the United States) together accounted for carbon emissions from fossil-fuel combustion of approximately 1.86 ± 0.2 Gt C, or about 27% of the global total. The United States, the world's largest emitter of carbon dioxide, was responsible for 86% of the North American total. Per capita emissions in 2003 were 5.4 ± 0.5 metric ton in the United States, 5.0 ± 0.55 metric ton in Canada, and 0.9 ± 0.1 metric ton 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, 2005). The world's largest countries, China and India, have total carbon emissions from fossil-fuel combustion and the flaring of natural gas that are substantially lower than those in the United States. The 2003 total for China was 61% of that in the United States, and the total for India was 18% that of the United States. Per capita emissions for China and India in 2003 were 14% and 5%, respectively, of the U.S. rate (DOE EIA, 2005).

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 (Wanninkhof and McGillis, 1999), 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 Gt of anthropogenic carbon has entered the oceans (Sabine *et al*., 2004a) and that forests in the mid-latitudes of the Northern Hemisphere sequestered 0.6 to 0.7 Gt C yr^{-1} in the 1990s (Goodale *et al*., 2002). Changes in the atmospheric inventory of O_2 (Keeling *et al*., 1996) and ^{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 useful 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 (Broecker *et al*., 1980) (^{14}C and chlorofluorocarbons) 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 yr^{-1} (Greenblatt and Sarmiento, 2004), and while uncertainties on these estimates are about ±50%, they 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, for example deforestation, have been modeled based on historical land use (Houghton, 1999b). 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 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 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 injects an important connection with reality.

RECENT DYNAMICS OF THE UNMANAGED CARBON CYCLE

Of the approximately 466 ± 160 Gt carbon added to the atmosphere by human actions since 1850, 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 has now been identified in the oceans (Sabine *et al*., 2004a). This leaves about 161 ± 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 uptake by the oceans averaged 1.7 ± 0.3 Gt C yr^{-1} 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 anthropogenic flux is this amount, plus 0.45 Gt yr^{-1} of preindustrial outgasing, for a total of 2.2 ± 0.4 Gt yr^{-1}. This rate represents an integral over large areas that 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*., 2006). 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 approximately 1.1 Gt C yr^{-1}

(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 Mt. 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 (Fig. 2-3). Fire likely plays a large role in this variability (van der Werf *et al*., 2004).

Figure 2-3. The 13-model mean CO_2 flux interannual variability (Gt C yr^{-1}) for several continents (solid lines) and ocean basins (dashed lines). (A) North Pacific and North America, (B) Atlantic north of 15ºN and Eurasia, (C) Australasia and Tropical Pacific, (D) Africa, and (E) South America (note the different scales for Africa and South America) (from Baker *et al*., 2006).

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. CO_2 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, especially fertilization of plant growth by increased atmospheric CO_2. Recent evidence emphasizes the diversity of mechanisms.

The Carbon Cycle of North America

By most estimates, the land area of North America is currently a sink for carbon, in the absence of emissions from fossil-fuel combustion. 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

(Pacala *et al*., 2001) used a combination of atmospheric and land-based techniques to estimate that the 48 contiguous U.S. states are currently a carbon sink of 0.3 to 0.6 Gt C yr^{-1}. This estimate and a discussion of the processes responsible for recent sinks in North America are updated in chapter 3. Based on inversions using 13 atmospheric transport models, North America was a carbon sink of 0.97 Gt C yr^{-1} from 1991–2000 (Baker *et al*., 2006). Over the area of North America, this amounts to an annual carbon sink of 39.6 g C m^{-2} yr^{-1}, similar to the sink inferred for all northern lands (North America, Europe, Boreal Asia, and Temperate Asia) of 32.5 g C m^{-2} yr^{-1} (Baker *et al*., 2006).

Very little of the current carbon sink in North America is a consequence of deliberate action to 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.

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 a decrease 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). Costs of this kind of effort would, however, include the loss of the new forested area from its previous uses, including grazing or agriculture, plus the energy costs of managing the new forests, plus any increases in emissions of non-CO_2 greenhouse gases from the new forests. Large-scale investments in biomass energy 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 emissions. 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). Nothing about the status of the unmanaged carbon cycle provides a justification for assuming that it can compensate for emissions from fossil fuel combustion.

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Table 1. Sinks of carbon for 1980–90 in the coterminous United States (in Gt C yr^{-1}).

Category	Low	High	Land area 1980–90 (10^6 ha)	Houghton *et al.* (8)	Birdsey and Heath (12)
Forest trees	0.11	0.15	247–247	0.06 [a]	0.11
Other forest organic matter	0.03	0.15	247–247	– 0.01	0.18
Cropland soils	0.00	0.04	185–183	0.14	—
Nonforest, non-cropland (woody encroachment)	0.12 [b]	0.13 [b]	334–336 [c]	0.12	—
Wood products	0.03	0.07	—	0.03	0.03
Reservoirs, alluvium, colluvium	0.01	0.04	—	—	—
Exports minus imports of food, wood	0.04	0.09	—	—	—
Fixed in the United States but exported by rivers	0.03	0.04	—	—	—
"Apparent"[d] U.S. sink without woody encroachment	0.25	0.58	766	0.15–0.23 [e]	0.31
"Apparent"[d] U.S. sink including woody encroachment	0.37	0.71	766	0.15–0.35 [e]	—
Sink [f]	0.03	0.58	766	0.15–0.35 [e]	0.31

[a] Assumes that the 0.05 Gt C yr^{-1} estimated in (8) to be accumulating in western pine woodlands as a result of the suppression is assigned to forest instead of row 4.
[b] These numbers are not bounds, but rather the only two existing estimates.
[c] Total area for all lands other than forest and croplands. Possible woody encroachment because of fire suppression on up to about two-thirds of this land (10,16).
[d] By "apparent" sink, we mean the net flux from the atmosphere to the land that would be estimated in an inversion. It includes all terms in the table.
[e] Lower bound reflects uncertainty in the estimates for the effects of fire suppression.
[f] Excludes sinks caused by the export/import imbalance for food and wood products and river exports because these create corresponding sources outside the United States.
Source: Pacala *et al*. (2001)

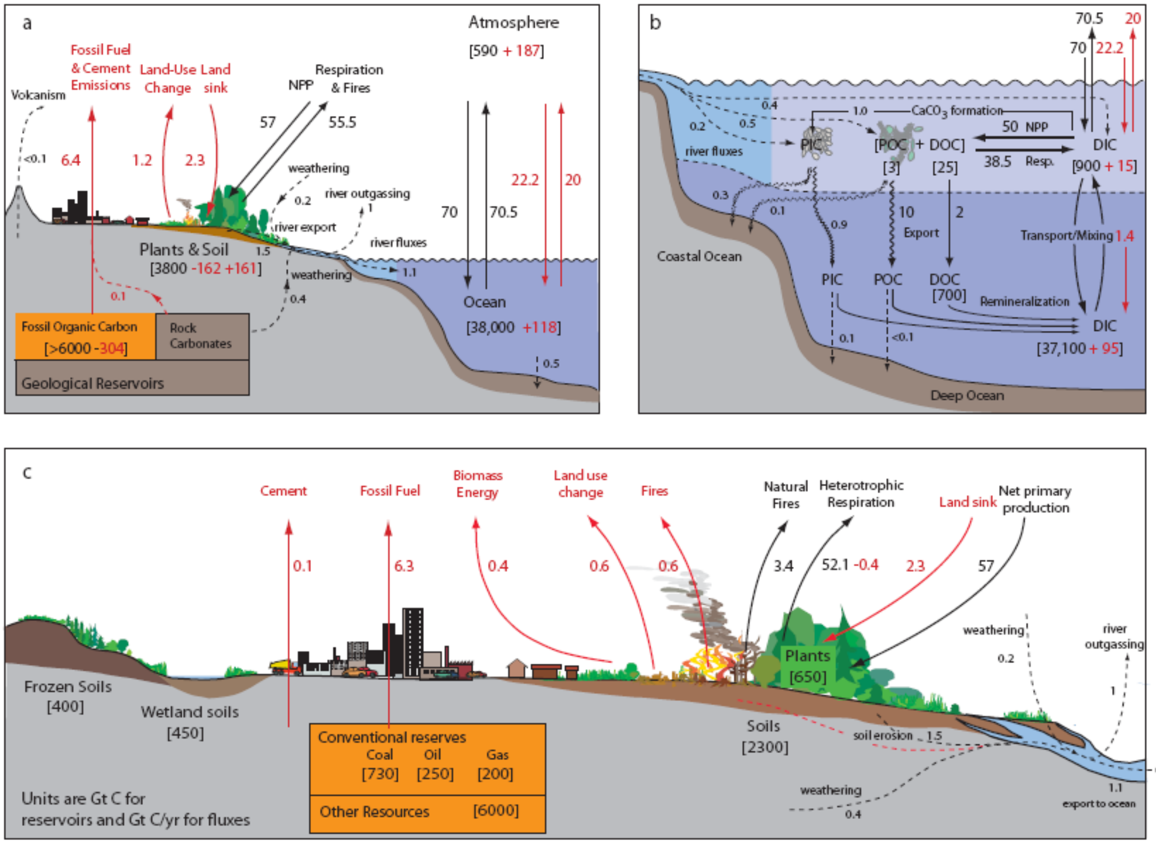

Figure 2-1. Schematic representation of the components of the global carbon cycle. The three panels show (A) the overall cycle, (B) the details of the ocean cycle, and (C) and the details of the land cycle. For all panels, carbon stocks are in brackets, and fluxes have no brackets. Pre-anthropogenic stocks and fluxes are in black. Anthropogenic perturbations are in red. For stocks, the anthropogenic perturbations are the cumulative total since 1850. Anthropogenic fluxes are means for the 1990s. Redrawn from Sabine *et al*. (2004b) with updates as discussed in the text.

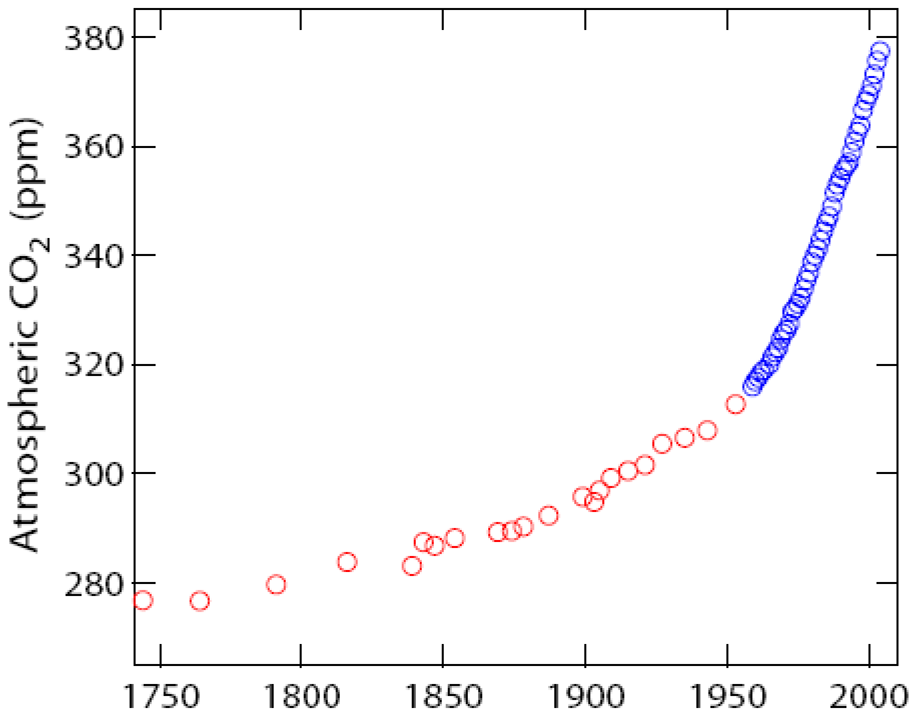

Fig. 2-2. Atmospheric CO_2 concentration from 1850 to 2005. The data prior to 1957 (red circles) are from the Siple ice core (Friedli *et al.*, 1986). The data since 1957 (blue circles) are from continuous atmospheric sampling at the Mauna Loa Observatory (Hawaii) (Keeling *et al.*, 1976; Thoning *et al.*, 1989) (with updates available at http://cdiac.ornl.gov/trends/co2/sio-mlo.htm).

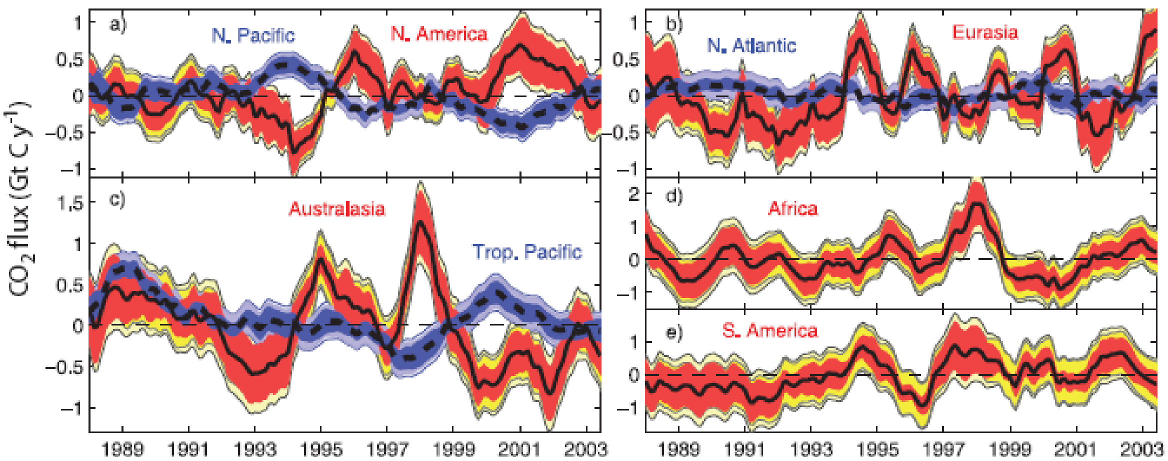

Figure 2-3. The 13-model mean CO_2 flux interannual variability (Gt C yr^{-1}) for several continents (solid lines) and ocean basins (dashed lines). (A) North Pacific and North America, (B) Atlantic north of 15ºN and Eurasia, (C) Australasia and Tropical Pacific, (D) Africa, and (E) South America (note the different scales for Africa and South America) [from (Baker *et al*., 2006)].

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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 Mt C yr^{-1} in 2003 This represents 27% of global fossil fuel emissions.
- Approximately 30% of North American fossil fuel emissions are offset by a natural sink of 592 Mt C yr^{-1} caused by a variety of factors, including forest regrowth, fire suppression, and agricultural soil conservation.
- North American carbon dioxide emissions from fossil fuel have increased at an average rate of approximately 1% per year for the last 30 years.
- The 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.
- Historically the plants and soils of the United States and Canada were sources for atmospheric CO2, primarily as a consequence of the expansion of croplands into forests and grasslands. In recent

decades the terrestrial carbon balance of these regions have shifted from source to sink as forests recover from agricultural abandonment, fire suppression and reduced logging and, as a result, are accumulating carbons. In Mexico, emissions of carbon continue to increase from net deforestation.

- Fossil fuel emissions from North America are expected to continue to grow, but will also continue to grow more slowly than GDP.
- 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 CO2 concentrations in the atmosphere, nor do we understand the impact of tropospheric ozone or how the sink will change as the climate changes.
- The 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 U.S. 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.

Fossil Fuel

Fossil fuel carbon emissions in the United States, Canada, and Mexico totaled 1856 Mt C yr^{-1} 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 yr^{-1}, see Fig. 3-1). 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 US Energy Information Administration (EIA 2005).

The United States is the world's largest emitter in absolute terms. Its per capita emissions of 5.4 t C yr^{-1} are among the largest in the world, 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 U.S. emissions have grown at close to the North American average rate of about 1.0% per year over the past 30 years, but U.S. per capita emissions have been roughly constant, while the carbon intensity of the U.S. economy has decreased at a rate of about 2% per year (see Figs. 3-1 to 3-5).

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 U.S. 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) (Fig. 3-3, 3-4 and 3-5).

Historical decreases in U.S. carbon intensity began early in the 20th century and continue despite the approximate stabilization of per capita emissions (Fig. 3-2). Why has the U.S. carbon intensity declined? This question is the subject of the extensive literature on the so-called structural decomposition of the energy system and on the relationship between GDP and 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 U.S. 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 by gas, or coal 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 (Fig. 3-4). Because the service sector has a much lower carbon intensity than manufacturing (a factor of 6.5 in 2002; compare Figs. 3-4 and 3-5), 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%. 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 that emissions growth is essentially decoupled from economic growth and speaks to the issue of our technological readiness to achieve an emissions target. For example, a portfolio of 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 emissions from manufacturing are approximately constant despite 1.5% economic growth, while those of services grew at 2.1% despite 3.6% economic growth (Figs. 3-3 and 3-4). The decrease in the carbon intensity within these sectors 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 (Fig. 3-4; 30-year average of 1.0% per year), while emissions from transportation are growing faster than the population but slower than GDP (Fig. 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).

Figure 3-2. The historical relationship between U.S. per capita GDP and U.S. 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 red square farthest to the right shows U.S. 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).

Figure 3-3. Historical U.S. GDP divided among the manufacturing, services and agricultural sectors. *Source*: Mitchell (1998) and WRI (2005).

Figure 3-4. Historical U.S. carbon emissions divided among the residential, commercial, industrial, and transportation sectors. *Source*: EIA (2005).

Carbon Sinks (see Tables 3-1and 3-2 for citations and data)

Approximately 30% of North American fossil fuel emissions are offset by a natural sink of 592 Mt C yr^{-1} caused by a variety of factors, including forest regrowth, fire suppression, and agricultural soil conservation. The sink currently absorbs 506 Mt C yr^{-1} in the United States and 134 Mt C yr^{-1} in Canada. Mexican ecosystems create a net source of 48 Mt C yr^{-1}. Rivers and international trade also export a net of 161 Mt C yr^{-1} that was captured from the atmosphere by the continent's ecosystems, and so North America absorbs 753 Mt C yr^{-1} of atmospheric CO_2 (753 = 592 + 161). Because most of these net exports will return 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 592 Mt C yr^{-1} even though the continent absorbs a net of 753 Mt C yr^{-1}. Moreover, coastal waters may be small net emitters to the atmosphere at the continental scale (19 Mt C yr^{-1}), but this flux is highly uncertain (see Chapter 15). The portion of the coastal flux caused by human activity is thought to be close to zero, and so coastal sea-air exchanges should also be excluded from the continental carbon sink.

As reported in Chapter 2, the United States is responsible for 27% of the global carbon sink and 86% of the North American sink. The reason for the disproportionate importance of U.S. sinks is probably the unique land use history of the country (summary in Appendix 3A). 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 U.S. sink (Houghton *et al*., 2000). Most of the U.S. 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).

Table 3-1. Annual net carbon emissions (source = positive) or uptake (land sink = negative) of carbon in millions of tons.

Table 3-2. Annual net horizontal transfers of carbon in millions of tons.

Table 3-3. Carbon stocks in North America in billions of tons.

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. We report uncertainties using six categories: ***** = 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%, * = uncertainty > 100%.

In addition to inventory methods, it is also possible to estimate carbon sources and sinks by measuring carbon dioxide 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 U.S. 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 yr^{-1}). The appropriate inventory-based estimate to compare this to is our –753 Mt C yr^{-1} 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*., 2000). 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 U.S. 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 inter-annual variation the continental flux of carbon.

The 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 U.S. 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 U.S. sink than would any other measurement program of similar cost. Also we still lack comprehensive U.S. 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 Table 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 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 the rate of decomposition of dead organic matter, which should decrease the sink. The relative strength of these two 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.

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 yr^{-1} (Smith and Heath, 2005, uncertainty ****) plus 23 Mt C yr^{-1} 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 –259 Mt C yr^{-1} and includes a sink of 90 Mt C yr^{-1} (uncertainty **) from the accumulation of nonliving carbon in the soil (-90-146-23 = –259) (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 carbon dioxide 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 3B, 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, 2005), managed forests in Canada (comprising 53% of the total forest area) sequestered 101 Mt C aboveground in 1990 (uncertainty ***). Since then, carbon sequestration has decreased gradually to 69 Mt C in 2003, as managed forests have recovered from past disturbances (Kurz and Apps, 1999, uncertainty ***). In addition, Goodale *et al*. (2002) estimate the sink of nonliving carbon belowground to be –30 Mt C yr^{-1} for the period 1990–1994 (uncertainty **).

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.

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 yr^{-1} in the United States (Skog and Nicholson, 1998) and –10 Mt C yr^{-1} in Canada (Goodale *et al*., 2002). We know of no estimates for Mexico.

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 gains and losses are 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 U.S. woody encroachment sink (Kulshreshtha *et al*., 2000; Houghton and Hackler, 1999; 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 yr^{-1} in Table 3-1 is from Kulshreshtha *et al*. (2000) but is similar to the estimates from the other two studies (–120 and –130 Mt C yr^{-1}). 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.

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 (see Chapter 10), have reversed the losses of carbon on some croplands, but the losses continue on the remaining lands. The net is an approximate carbon balance for agricultural soils in Canada and estimates for the United States ranging from a small source of 2Mt C yr^{-1} to small sink of -6 Mt C yr^{-1}.

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 between –19 and –20 Mt C yr^{-1} (see Chapters 12 and 13), but drainage of U.S. peatlands have created a net source of 5 Mt C yr^{-1}. 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 Gt C) during this century if released because of global warming (see the model result in Cox *et al*., 2000 for an example).

The carbon sink due to sedimentation in wetlands is between 0 and –21 Mt C yr^{-1} in Canada and between 0 and –112 Mt C yr^{-1} in the United States (see Chapter 13). 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 carbon dioxide; 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 as peat in Canada and make U.S. wetlands a source of warming on a decadal time scale (Chapter 13). Moreover, if wetlands become warmer and remain wet with future climate change, they have the potential to emit large amounts of methane. This is probably the single most important consideration, and unknown, in the role of wetlands and future climate change.

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 yr^{-1} in the coterminous United States. This analysis has also recently been repeated and produced an estimate of 17 Mt C yr^{-1} (E. Sundquist, personal communication). We know of no similar analysis for Canada or Mexico.

Exports Minus Imports of Wood and Agricultural Products

The United States imports 14 Mt C yr^{-1} more wood products than it exports and exports 30–50 Mt C yr^{-1} more agricultural products 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 yr^{-1} (Environment Canada, 2005) and Mexico at –1 Mt C yr^{-1} (Masera *et al*., 1997). We know of no analysis of the Canadian or Mexican export-import balance for agricultural products.

River Export

Rivers in the coterminous United States were estimated to export 30–40 Mt C yr^{-1} 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 yr^{-1} 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.

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 U.S. 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 for carbon management in coastal waters of North America.

CONCLUDING SUMMARY

Fossil fuel emissions currently dominate the net carbon balance in the United States, Canada, and Mexico (Fig. 3-1, Tables 3-1, 3-2). U.S. fossil fuel consumption currently emits 1582 Mt C yr^{-1} to the atmosphere. This is partially balanced by a flow of 506 Mt C yr^{-1} from the atmosphere to land caused by net ecosystem sinks in the United States. Canadian fossil consumption transfers 164 Mt C yr^{-1} to the atmosphere, but net ecological sinks capture 134 Mt C yr^{-1}. Mexican fossil emissions of 110 Mt C yr^{-1} are supplemented by a net ecosystem source of 48 Mt C yr^{-1} from tropical deforestation. Each of the three countries has always been a net source of carbon dioxide emissions to the atmosphere for the past three centuries (Houghton *et al*., 1999, 2000; Houghton and Hackler, 2000; Hurtt *et al*., 2002).

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Table 3-1. Annual net emissions (source = positive) or uptake (land sink = negative) of carbon in millions of tons

Source (positive) or Sink (negative)	United States	Canada	Mexico	North America
Fossil source (positive)				
Fossil fuel [a] (oil, gas, coal)	1582[****] (681, 328, 573)	164[****] (75, 48, 40)	110[****] (71, 29, 11)	1857[****] (828, 405, 624)
Nonfossil carbon sink (negative) or source (positive)				
Forest	–259[b,***]	–99[c,***]	+52[d,**]	–306[***]
Wood products	–57[e,***]	–10[f,***]	ND	–67,***
Woody encroachment	–120[g,*]	ND	ND	–120[*]
Agricultural soils	–4[h,*]	–0[h]	–0[h]	–4[*]
Wetlands	–41[i,*]	–25[i,*]	–4[i,*]	–70[*]
Rivers and reservoirs	–25[j,**]	ND	ND	–25[*]
Total carbon source or sink	–506[***]	–134[**]	48[*]	–592[***]

Uncertainty:

*****(95% confidence within 10%)
****(95% confidence within 25%)
***(95% confidence within 50%)
**(95% confidence within 100%)
*(95% confidence bounds >100%)
ND = No data available
[a]http://www.eia.doe.gov/env/inlenv.htm
[b]Smith and Heath (2005) for above ground carbon, but including 23 Mt C/yr^{-1} for U.S. urban and suburban forests from Chapter 14, and Pacala *et al*. (2001) for below ground carbon.
[c]Environment Canada (2005)
[d]Masera *et al.* (1997)
[e]Skog *et al*. (2004), Skog and Nicholson (1998)
[f]Goodale *et al.* (2002)
[g]Kulshreshtha *et al*. (2000), Hurtt *et al*. (2002), Houghton and Hackler (1999).
[h]Chapter 10; Highly uncertain; Could range from -5 Mt C yr^{-1} to 5 Mt C yr^{-1}.
[i]Chapter 13
[j]Stallard, 1998; Pacala *et al*. (2001)

Table 3-2. Annual net horizontal transfers of carbon in millions of tons.

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)	–592[***]	–208[**]	47[*]	–753[**]
Net absorption (negative) or emission (positive) by coastal waters	ND	ND	ND	19[e,*]

Uncertainty:

*****(95% confidence within 10%)
****(95% confidence within 25%)
***(95% confidence within 50%)
**(95% confidence within 100%)
*(95% confidence bounds >100%)
ND = No data available
[a]Environment Canada (2005)
[b]Masera *et al.* (1997)
[c]Skog *et al*. (2004), Skog and Nicholson (1998)
[d]Pacala et al. (2001)
[e]Chapter 15

Table 3-3. Carbon stocks in North America in billions of tons

	United States	Canada	Mexico	North America
Forest	53[a,***]	85[a,***]	9[d,**]	147[***]
Cropland	14[b,****]	4[b,****]	1[b,**]	19[****]
Pasture	33[b,***]	12[b,***]	10[b,***]	55[***]
Wetlands	42[c,***]	152[c,***]	2[c,*]	196[***]
Total	142[***]	253[***]	22[**]	417[***]

Uncertainty:

*****(95% confidence within 10%)
****(95% confidence within 25%)
***(95% confidence within 50%)
**(95% confidence within 100%)
*(95% confidence bounds >100%)

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

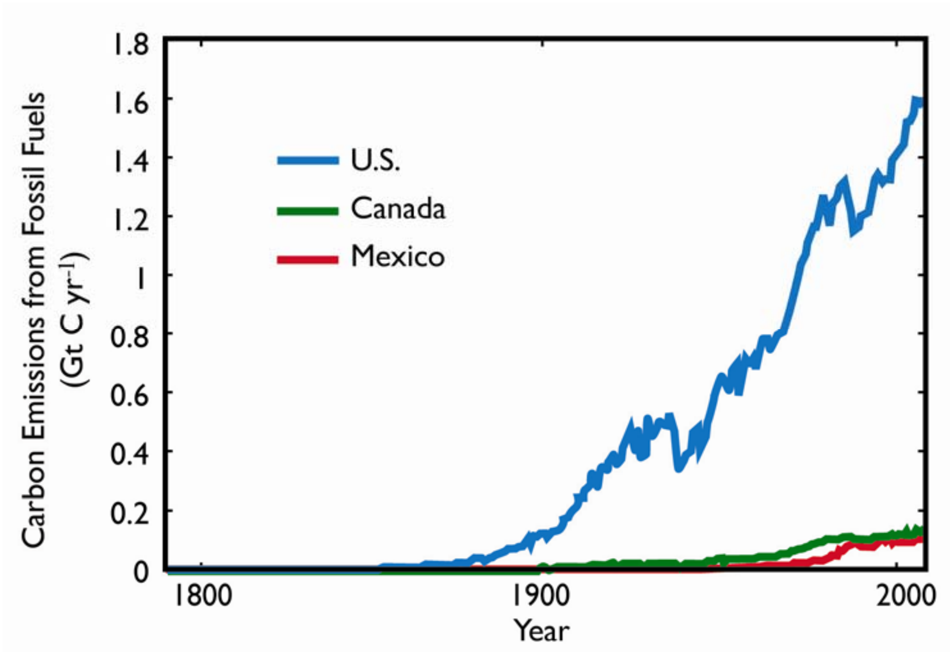

Fig. 3-1. Historical carbon emissions from fossil fuel in the United States, Canada, and Mexico. Data from the U.S. Energy Information Administration (EIA 2005).

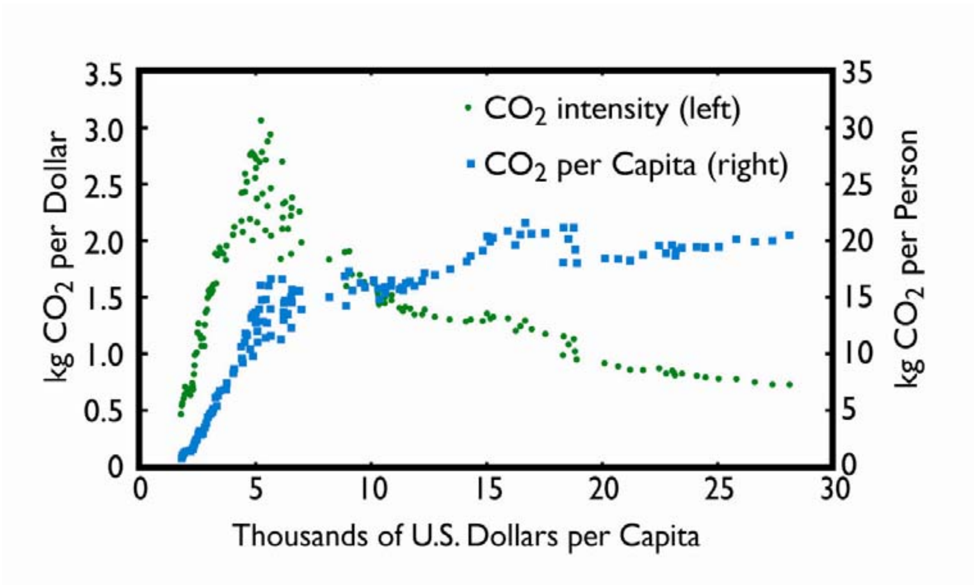

Fig. 3-2. The historical relationship between U.S. per capita GDP and U.S. carbon intensity (green symbols, kg CO_2 emitted per 1995 dollar of GDP) and per capita carbon emissions (blue symbols, kg CO_2 per person). Each symbol shows a different year and each of the two time series progresses roughly chronologically from left (early) to right (late) and ends in 2002. *Source*: Maddison (2003), Marland *et al*. (2005). Thus, the red square farthest to the right shows U.S. 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).

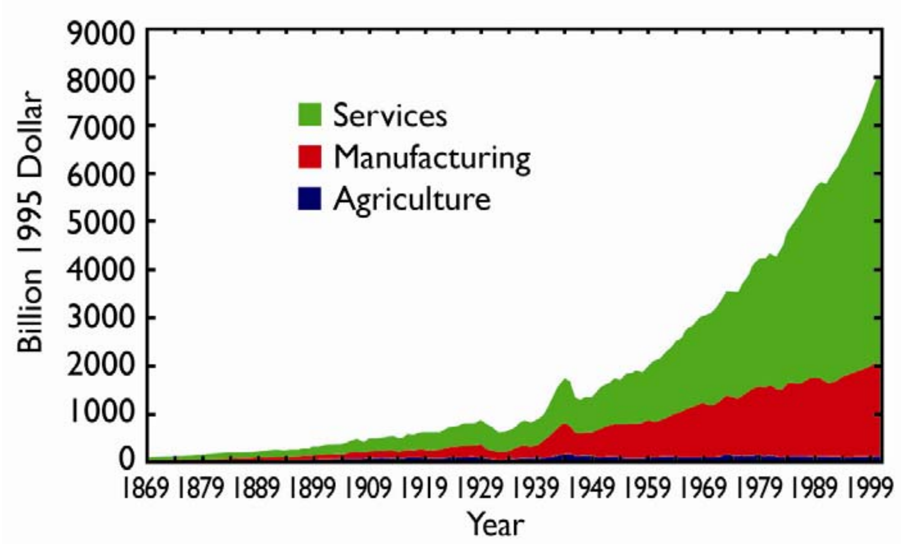

Figure 3-3. Historical U.S. GDP divided among the manufacturing, services, and agricultural sectors.

Source: Mitchell (1998), WRI (2005).

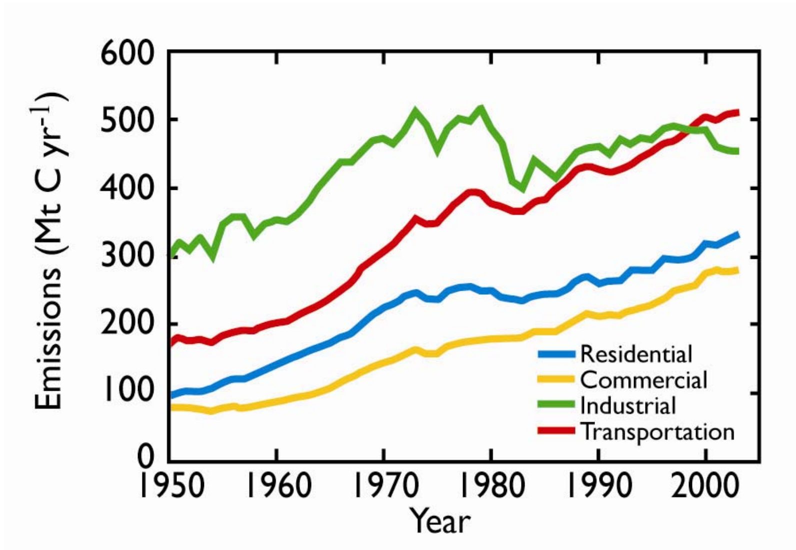

Figure 3-4. Historical U.S. carbon emissions divided among the residential, services, manufacturing, and transportation sectors. *Source*: EIA (2005).

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Appendix 3A

Historical Overview of the Development of U.S., Canadian, and Mexican Ecosystem Sources and Sinks for Atmospheric Carbon

Although the lands of the New World were inhabited before the arrival of Europeans, the changes since arrival have been enormous, especially during the last two centuries. Peak U.S. emissions from land-use change occurred late in the 19th century, and the last few decades have experienced a carbon sink (Houghton *et al*., 1999; Hurtt *et al*., 2002). In Canada, peak emissions occurred nearly a century later than in the United States, and current data show that land-use change causes a net carbon sink (Environment Canada, 2005). In Mexico, the emissions of carbon continue to increase from net deforestation. All three countries may be in different stages of the same development pattern (see Fig. 3-2).

The largest changes in land use and the largest emissions of carbon came from the expansion of croplands. In addition to the carbon lost from trees, soils lose 25–30% of their initial carbon content (to a depth of 1 m) when cultivated. In the United States, croplands increased from about 0.25 million ha in 1700 to 236 million ha in 1990 (Houghton *et al*., 1999; Houghton and Hackler, 2000). The most rapid expansion (and the largest emissions) occurred between 1800 and 1900, and since 1920 there has been little net change in cropland area. Pastures expanded nearly as much, from 0.01 million to 231 million ha, most of the increase taking place between 1850 and 1950. As most pastures were derived from grasslands, the associated changes in carbon stocks were modest.

The total area of forests and woodlands in the United States declined as a result of agricultural expansion by 160 million ha (38%), but this net change obscures the dynamics of forest loss and recovery, especially in the eastern part of the United States. After 1920, forest areas increased by 14 million ha nationwide as farmlands continued to be abandoned in the northeast, southeast, and north central regions. Nevertheless, another 4 million ha of forest were lost in other regions, and the net recovery of 10 million ha offset only 6% of the net loss (Houghton and Hackler, 2000).

Between 1938 and 2002, the total area of forest land in the conterminous United States decreased slightly, by 3 million ha (Smith *et al*., 2004). This small change is the net result of much larger shifts among land-use classes (Birdsey and Lewis, 2003). Gains of forest land, primarily from cropland and pasture, were about 50 million ha for this period. Losses of forest land to cropland, pasture, and developed use were about 53 million ha for the same period. Gains of forest land were primarily in the

Eastern United States, whereas losses to cropland and pasture were predominantly in the South, and losses to developed use were spread around all regions of the United States.

In the United States, harvest of industrial wood (timber) generally followed the periods of major agricultural clearing in each region. In the last few decades, total volume harvested increased until a recent leveling took place (Smith *et al*., 2004). The volume harvested in the Pacific Coast and Rocky Mountain regions has declined sharply, whereas harvest in the South increased and in the North, stayed level. Fuel wood harvest peaked between 1860 and 1880, after which fossil fuels became the dominant type of fuel (Houghton and Hackler, 2000).

The arrival of Europeans reduced the area annually burned, but a federal program of fire protection was not established until early in the 20th century. Fire exclusion had begun earlier in California and in parts of the central, mountain and Pacific regions. However, neither the extent nor the timing of early fire exclusion is well known. After about 1920, the Cooperative Fire Protection Program gradually reduced the areas annually burned by wildfires (Houghton *et al*., 1999, 2000). The reduction in wildfires led to an increase in carbon storage in forests. How long this "recovery" will last is unclear. There is some evidence that fires are becoming more widespread, again, especially in Canada and the western United States. Fire exclusion and suppression are also thought to have led to woody encroachment, especially in the southwestern and western United States. The extent and rate of this process is poorly documented, however, and estimates of a carbon sink are very uncertain. Gains in carbon aboveground may be offset by losses belowground in some systems, and the spread of exotic annual grasses into semiarid deserts and shrublands may be converting the recent sink to a source (Bradley *et al*., in preparation).

The consequence of this land-use history is that U.S. forests, at present, are recovering from agricultural abandonment, fire suppression, and reduced logging (in some regions), and, as a result, are accumulating carbon (Birdsey and Heath, 1995; Houghton *et al*., 1999; Caspersen *et al*., 2000; Pacala *et al*., 2001). The magnitude of the sink is uncertain, and whether any of it has been enhanced by environmental change (CO_2 fertilization, nitrogen deposition, and changes in climate) is unclear. Understanding the mechanisms responsible for the current sink is important for predicting its future behavior (Hurtt *et al.,* 2002).

In the mid-1980s, Mexico lost approximately 668,000 ha of closed forests annually, about 75% of them tropical forests (Masera *et al*., 1997). Most deforestation was for pastures. Another 136,000 ha of forest suffered major perturbations, and the net flux of carbon from deforestation, logging, fires, degradation, and the establishment of plantations was 52.3 Mt C yr^{-1}, about 40% of the country's estimated annual emissions of carbon. A later study found the deforestation rate for tropical Mexico to be about 12% higher (1.9% per year) (Cairns *et al*., 2000).

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Appendix 3B

Eddy-Covariance Measurements Now Confirm Estimates of Carbon Sinks from Forest Inventories

Long-term, tower-based, eddy-covariance measurements (e.g., Wofsy *et al*., 1993) represent an independent approach to measuring ecosystem-atmosphere CO_2 exchange. The method describes fluxes over areas of approximately 1 km^2 (Horst and Weil, 1994), measures hour-by-hour ecosystem carbon fluxes, and can be integrated over time scales of years. A network of more than 200 sites now exists globally (Baldocchi *et al*., 2001); more than 50 of these are in North America. None of these sites existed in 1990, so these represent a relatively new source of information about the terrestrial carbon cycle. An increasing number of these measurement sites include concurrent carbon inventory measurements.

Where eddy-covariance and inventory measurements are concurrent, the rates of accumulation or loss of biomass are often consistent to within several tens of g C m^{-2} yr^{-1} for a one-year sample (10 g C yr^{-1} is 5% of a typical net sink of 2 metric tons of carbon per hectare per year for an Eastern deciduous successional forest) . Published intercomparisons in North America exist for western coniferous forests (Law *et al*., 2001), agricultural sites (Verma *et al*., 2005), and eastern deciduous forests (Barford *et al*., 2001; Cook *et al*., 2004; Curtis *et al*., 2002; Ehmann *et al*., 2002; Gough *et al*., in review). Multiyear studies at two sites (Barford *et al*., 2001; Gough *et al*., in review) show that 5- to 10-year averages converge toward inventory measurements. Table 3B-1 from Barford *et al*. (2001) shows the results of nearly a decade of concurrent measurements in an eastern deciduous forest.

This concurrence between eddy-covariance flux measurements and ecosystem carbon inventories is relevant because it provides independent validation of the inventory measurements used to estimate long-term trends in carbon stocks. The eddy-covariance data are also valuable because the assembly of global eddy-covariance data provides independent support for net storage of carbon by many terrestrial ecosystems and the substantial year-to-year variability in this net sink. The existence of the eddy-covariance data also makes the sites suitable for co-locating mechanistic studies of inter-annual and shorter, time-scale processes governing the terrestrial carbon cycle. Chronosequences show trends consistent with inventory assessments of forest growth, and comparisons across space and plant functional types are beginning to show broad consistency. These results show a consistency across a mixture of observational methods with complementary characteristics, which should facilitate the development of an increasingly complete understanding of continental carbon dynamics (Canadell *et al*., 2000).

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Table 3B-1. Carbon budget for Harvard Forest from forest inventory and eddy-covariance flux measurements, 1993–2001. *Source*: Barford *et al.* (2001), Table 1. Numbers in parentheses give the ranges of the 95% confidence intervals.

Component	Change in carbon stock or flux (g C m^{-2} yr^{-1})	Totals
Change in live biomass		
A. Aboveground		
1. Growth	1.4 (±0.2)	
2. Mortality	–0.6 (±0.6)	
B. Belowground (estimated)		
1. Growth	0.3	
2. Mortality	–0.1	
Subtotal		1.0 (±0.2)
Change in dead wood		
A. Mortality		
1. Aboveground	0.6 (±0.6)	
2. Belowground	0.1	
B. Respiration	–0.3 (±0.3)	
Subtotal		0.4 (±0.3)
Change in soil carbon (net)		0.2 (±0.1)
Sum of carbon budget figures		1.6 (±0.4)
Sum of eddy-covariance flux measurements		2.0 (±0.4)

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Chapter 4. What Are the Options and Measures That Could Significantly Affect the Carbon Cycle?

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KEY FINDINGS

- Options to reduce energy-related CO_2 emissions include improved efficiency, fuel switching (among fossil fuels and non-carbon fuels), and CO_2 capture and storage.
- 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. This means that cost-effective reduction of energy-related CO_2 emissions may best be achieved as existing equipment and facilities are replaced. It also means that technological change will have a significant impact on the cost because emission reductions will be implemented over a long time.
- 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 small relative to the excess carbon in the atmosphere. These options can be implemented in the short-term, but the amount of carbon sequestered typically is low initially then rising 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.
- A number of policy options can help reduce carbon emissions and increase carbon sinks. The effectiveness of a policy depends on the technical feasibility and cost-effectiveness of the portfolio of measures 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 CO_2 concentrations cost effectively in the short- and long-term would: (1) encourage adoption of cost-effective emission reduction and sink enhancement measures through an emissions trading program or an emissions tax; (2) stimulate development of technologies that

lower the cost of emissions reduction, geological storage and sink enhancement; (3) adopt appropriate regulations to complement the emissions trading program or emission tax for sources or actions subject to market imperfections, such as energy efficiency measures and co-generation; (4) Revise existing policies with other objectives that lead to higher CO_2 or CH_4 emissions so that the objectives, if still relevant, are achieved with lower emissions.

- Implementation of such policies is best achieved by national governments with international cooperation. This provides maximum coverage of CO_2 emissions and carbon sinks and so enables implementation of the most cost-effective options. It also allows better allocation of resources for technology research and development. National policies may need to be coordinated with state/provincial governments, or state/provincial governments may implement coordinated policies without the national government.

INTRODUCTION

This chapter provides an overview of measures 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 measures.

SOURCE REDUCTION OPTIONS

Energy-Related CO_2 Emissions

Combustion of fossil fuels is the main source of CO_2 emissions, 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).

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, 2001a).[1] That entails a transition to an energy system 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. The transition to such an energy system, while meeting growing energy needs, will take at least several decades. Thus, shorter term (2015–2025) and longer term (post-2050) options are differentiated.

[1]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.

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 and to non-carbon fuels, and
- switching to electricity and hydrogen produced from fossil fuels in processes with CO_2 capture and geological storage.

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.[2] 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.[3] 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.[4] 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 too expensive to warrant implementation. Market imperfections inhibit adoption of some cost-effective efficiency improvements (NCEP, 2005).[5]

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.[6] 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 technological developments.

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[2] 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 measures that reduce transportation demand, such as telecommuting and designing communities so that people live closer to shopping and places of work.

[3] 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.

[4] 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.

[5] Examples include limited foresight, externalities, capital market barriers, and principal/agent split incentive problems.

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

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 for fossil fuels (carbon intensity) 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 refueling infrastructure.

Non-carbon 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 of the biomass fuel, and the carbon content of the fuel displaced.[7]

Carbon-free energy sources include hydro, wind, solar, biomass, geothermal, and nuclear fission.[8] Sometimes they are used to provide energy services directly, such as solar water heating and wind mills 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.

[7]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).

Electricity and Hydrogen from Fossil Fuels with CO_2 Capture and Geological 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, 2003). 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. 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 natural gas in most energy uses and 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.[9] 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. While most of the basic technology exists, much work remains too safely and cost effectively integrates CO_2 capture and storage into our energy system, so this is mainly a long-term option (IPCC, 2005).

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. CO_2 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.

Methane Emissions

Methane (CH_4) 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 methane can be collected

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

and used as an energy source. Methane emissions also occur during production of coal, oil, and natural gas. Such emissions usually can be flared or collected for use as an energy source.[10] 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 reductions are currently available.

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, 2000b). Currently, very large volumes of carbon are sequestered in the plant cells of the earth's forests. Increasing the stock of forest through afforestation[11], 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.

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. 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.

Although forest growth and soil sequestration cannot capture all of the excess carbon in the atmosphere, they do have the potential to capture a significant portion.[12] These options can be implemented in the short-term, but the amount of carbon sequestered typically is low initially then rising for a number of years before tapering off again as the total potential is achieved.

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[9]Since combustion of biomass releases carbon previously removed from the atmosphere, capture and storage of these emissions results in negative emissions.

[10]Flaring or combustion of methane as an energy source produces CO_2 emissions.

[11]Afforestation is the establishment of forest on land that has been unforested for a long time.

[12]The IPCC (2001b) estimated that biological growth including soils has the potential of capturing up to 20% of the globe's releases of excess atmospheric carbon over the next 50 years (Chapter 4). Nabuurs *et al.* (2000) estimate potential annual forest sequestration in the United States at 6% to 11% of 1990 emissions and 125% to 185% of 1990 emissions for Canada. For the two countries together, the figure is 17% to 27%.

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 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 the 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 previously cited, on other measures, 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 selected to implement 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, more for 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.

TEXT BOX on "Emission Reduction Supply Curve" goes here

The estimated cost and emission reduction potential for the principal short-term CO_2 emission reduction and sequestration options are summarized in Table 4-1. All estimates are expressed in 2004

U.S. dollars per metric ton of carbon.[13] The limitations of emission reduction supply curves noted in the text box apply equally to the cost estimates in Table 4-1.

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)].

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, 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 range. Finally, some categories include multiple options, notably those for the U.S. 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. 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, along with some estimates of their impacts on costs.

As indicated in several segments of Table 4-1, costs are sensitive to the policy instrument used to implement the option. In general, the less restrictive the policy, the lower the cost. That is why the cost estimates for the Feebate are lower than the cost estimate for the CAFÉ standard. In a similar vein, costs are lowered 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 the global trading costs are lower than the industrialized country trading case for the U.S. economy.

[13] A metric ton (sometimes written as "tonne") is 1000 kg, which is 2205 lb or 1.1025 tons.

[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.

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 cheap options become more costly with additional installations, and technological change lowers the costs of more expensive options. It is unlikely that policy-makers can identify the least-cost combination of options to achieve a given emission target. They can adopt policies, such as emissions trading or emissions taxes, that cover a large number of emitters and allow them to use their first-hand knowledge to choose the lowest cost reduction options.[15]

POLICY OPTIONS

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). Policies will need to stimulate implementation of a portfolio of options to reduce emissions and increase sequestration in the short-term, taking into account constraints on and implications of the mitigation strategies. The portfolio of short-term options will 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. Policies will also need to encourage 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.”

Because CO_2 has a long atmospheric residence time,[16] immediate action to reduce emissions and increase sequestration allows its atmospheric concentration to be stabilized at a lower level.[17] 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. Such policy instruments are discussed below.

The effectiveness of the policies is determined by the technical feasibility and cost-effectiveness of the portfolio of measures they seek to promote, their interaction with other policies that have unintended

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

[16]CO_2 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, 2001a, Table 1, p. 38)

[17]IPCC, 2001a, p. 187.

impacts on CO_2 emissions and by 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

- The institutional and timing aspects of technology transfer. The patenting system for instance does not allow all countries and sectors to get the best available technology.
- Demographic and social dynamics. Factors such as land tenure, population growth, and migration may pose an obstacle to afforestation/reforestation strategies.
- Institutional settings. The effectiveness of taxes, subsidies, and regulations to induce the deployment of certain technology may be limited by factors such as corruption or existence of vested interests.
- Environmental considerations. The portfolio of measures may incur environmental costs such as waste disposal or biodiversity reduction.

General Considerations

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). Voluntary agreements between industry and governments and information campaigns are politically attractive, raise awareness among stakeholders, and have played a role in the evolution of many national policies, but to date have generally yielded only modest results.[18] While some programs and agreements have reduced emissions, it appears that the majority of voluntary agreements have achieved limited emissions reductions beyond business as usual. (OECD, 2003b).

Reducing emissions will require the use of policy instruments such as regulations, emissions trading, and emissions taxes. 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 levels of energy efficiency of appliances, buildings, equipment, and vehicles.

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 excess 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. In a manner analogous to emissions trading, emitters will mitigate emissions up to the point

[18]Information and voluntary programs may have some impact on behavior through an appeal to patriotism or an environmental ethic; publishing information that may reveal negative actions, as in a pollutant registry; and providing public recognition, as in green labeling or DOE's Energy Star Program (Tietenberg and Wheeler, 2001).

where mitigation costs are lower than the tax, but once mitigation costs exceed the tax, they will opt to pay it.

The framework for choosing a policy instrument needs to consider technical, institutional and socioeconomic constraints that affect its implementation, such 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 conservation and other "no regrets" options), 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 ("general equilibrium" effects) and with existing policies. 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.[19] 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 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).[20] 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 (see, e.g., Rose and Oladosu, 2002).[21] A policy that raises revenue (an emissions tax or auctioned allowances) has a lower cost to the

[19]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.

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

[21]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.

economy than a policy that does not, if the revenue is used to reduce existing distortionary taxes[22] such as sales or income taxes (see, e.g., Parry *et al*., 1999).

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.[23]

Carbon dioxide emissions are well 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. The environmental impacts 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.

Despite the advantages of emissions trading and taxes, there are situations where regulations setting maximum emissions on individual sources or efficiency standards for appliances and equipment are preferred. 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 other barriers. Energy efficiency standards for appliances, buildings, equipment and vehicles tend to fall into this category (OECD, 2003a).[24] In some cases, such as refrigerators, standards have been used successfully to drive technology development.

Terrestrial Sequestration Policies

Currently there are few, if any, policies whose primary purpose is to increase carbon uptake by forests or agricultural soils. But policies designed to achieve other objectives, such as afforestation of marginal lands, green payments, conservation compliance, Conservation Reserve Program, and CSP increase

[22] 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.

[23] 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.

carbon uptake. 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.

Policies to increase carbon uptake by forests and agricultural soils could take the form of

- Regulations, such as requirements to reforest areas that have been logged, implement specified forest management practices, and establish land conservation reserves;
- Incentive-based policies, such as subsidies for adoption of specified forest management or agricultural practices, or issuance of tradable credits for increases in specified carbon stocks.[25] Since the carbon is easily released from these sinks, for example by a forest fire or tilling the soil, ensuring the permanence of the carbon sequestered is a major challenge for such policies. (Feng *et al*., 2003);[26]
- Voluntary actions, such as "best practices" that enhance carbon sequestration in soils and forests while realizing other benefits (e.g., managing forests for both timber and carbon storage), establishment of plantation forests for carbon sequestration, and increased production of wood products (Sedjo, 2001; Sedjo and Swallow, 2002).

The carbon cycle impacts of such programs would not be large, compared with emission levels; and in nearly every case they face serious challenges in verifying and monitoring the net carbon uptake, especially over relatively long periods (e.g., Marland *et al*., 2001).

Research and Development Policy

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

Two types of policies are needed to achieve a given cumulative CO_2 reduction or concentration target at least cost. Policies to reduce emissions and increase sequestration are needed to create a market for less

[24]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.

[25]There needs to be a buyer for the credits, such as sources subject to CO2 emissions trading program or an offset requirement. Determination of the quantity of credits earned requires resolution of many issues, including the baseline, leakage, and additionally. Projects to increase forest sequestration are envisaged in the Kyoto Protocol through Articles 3.3 and 3.4 and through the use of the Clean Development Mechanism (CDM).

[26]Agriculture and forestry credits could be temporary. Temporary credits could be valuable additions to a carbon reduction portfolio.

emission-intensive technologies. But direct support for research and development is also important; the combination of "research push" and "market pull" policies is more effective than either strategy on its own (Goulder, 2004). Policies should encourage research and development for all promising technologies because there is considerable ambiguity about which ones will ultimately prove most useful, socially acceptable, and cost-effective.[27]

CONCLUSIONS

Policies to reduce projected CO_2 and CH_4 concentrations in the atmosphere must 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 can adjust only slowly at reasonable cost;
- Potential uptake by agricultural soils and forests is significant but small relative to emissions and can be reversed easily at any given location by natural phenomena or human activities;
- 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; and
- Many policies implemented to achieve other objectives by different national, state/provincial, and municipal jurisdictions increase or reduce CO_2/CH_4 emissions.

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

- Encourage adoption of cost-effective emission reduction and sink enhancement measures. An emissions trading program or emissions tax that covers as many sources and sinks as possible, combined with regulations where appropriate, could achieve this. National policies can improve cost-effectiveness by providing broader coverage of sources and sinks while reducing adverse competitiveness effects. Use of revenue from auctioned allowances and emissions taxes to reduce existing distortionary taxes can reduce the economic cost of emission reduction policies.
- Stimulate development of technologies that lower the cost of emissions reduction, geological storage, and sink enhancement. Policies that encourage research, development, and dissemination of a portfolio of technologies combined with policies to reduce emissions and enhance sinks to create a "market pull" tend to be more effective than either type of policy alone.

[27] 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 is appropriate.

- Adopt appropriate regulations to complement the emissions trading program or emissions tax for sources or actions subject to market imperfections, such as energy-efficiency measures and co-generation. In some situations, credit trading can improve the efficiency of efficiency regulations.
- Revise existing policies at the national, state/provincial, and local level with other objectives that lead to higher CO_2 or CH_4 emissions so that the objectives, if still relevant, are achieved with lower emissions.

Implementation of such policies is best achieved by national governments with international cooperation. This provides maximum coverage of CO_2 and CH_4 emissions and carbon sinks. It also allows better allocation of resources for technology research and development. However, constitutional jurisdiction over emissions sources or carbon sinks may reside with state/provincial governments. In that case national policies may need to be coordinated with state/provincial governments, or state/provincial governments may implement coordinated policies without the national government.

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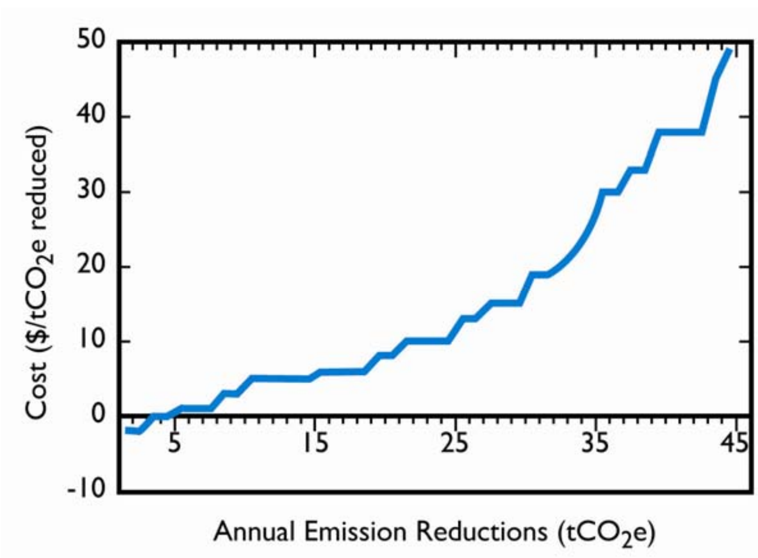
Emission Reduction Supply Curve

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. 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 measure 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. And the cost impact of having to implement additional measures due to underperformance by some measures 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.

[END OF TEXT BOX]

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 yr^{-1}) or % reduction	Source
Power generation	–$206 to 1067/t C	N.A.	DOE/EIA (2000)
Transportation/2010 (U.S. permit trading)	$76/t C	N.A.	DOE/EIA (2003)
Transportation/2025 (U.S. permit trading)	$214/t C	90	DOE/EIA (2003)
Transportation/2017 (CAFÉ standard)	$74/t C	43	US CBO (2003)
Transportation/2030 (Feebate)	$44/t C	74	Greene *et al*. (2005)
Afforestation/2010–2110	$54 to 109/t C	41 to 247	Lewandrowski (2004), Stavins and Richards (2005), EPA (2005)
Forest management/2010–2110	$4 to 109/t C	8 to 94	
Biofuels/2010–2110	$109 to181/t C	123 to 169	
Agricultural soil carbon sequestration/2010–2110	$4 to 109/t C	19 to 49	EPA (2005)
All industry			
Reduction of fugitives	$92 to 180/t C	3%	Hertzog (1999); Martin *et al*. (2001); Jaccard *et al*. (2002, 2003a, 2003b); Worrel *et al*. (2004); DOE (2006)
Energy efficiency	$0 to 180/t C	12% to 20%	
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 180/t C	90%	Hertzog (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 [a]	Not specified	EMF (2000)
Industrialized country trading	$19 to 299/t C [a]	Not specified	EMF (2000)
Global trading	$7 to 164/t C [a]	Not specified	EMF (2000)

Sources: Chapters 6–10 of this report.
[a]Annualized marginal cost (cost at upper limit of application, and therefore typically higher than average cost).

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Chapter 5. How can we improve the usefulness of carbon science for decision-making?

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KEY FINDINGS

- Decision-makers are beginning to seek 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 a 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 “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.

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, 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, 2001). In response, environmental advocates, business executives, and policy-makers have increasingly recognized the need to deliberately manage the carbon cycle. 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, sequestration, and impacts. This reflects that, until recently, scientists have approached carbon cycle science as basic science and non-scientist decision-makers have not 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. In particular, scientists and decision-makers will need to identify the information most needed in specific sectors for carbon management, to adjust research priorities, and to develop mechanisms that enhance the credibility of the information generated and the responsiveness of the information-generating process to stakeholder's views (Mitchell *et al*., 2006; Cash *et al*., 2003). Combining some "applied" or "solutions-oriented" research with a basic science portfolio would make carbon science more directly relevant to decision-making.

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 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.

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 Text Box 1).

CURRENT APPROACHES AND TRENDS

As we enter an era of deliberate carbon management, 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 (Government of Canada, 2005). For example, Canada's national government

[1]For examples, see Text Box 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/]

recently entered a research partnership with the province of Alberta, to assess geological sequestration of carbon dioxide, to develop fuel cell technologies using hydrogen, and to expand the use of biomass and biowaste for energy production (Government of Canada 2006).

Some stakeholders in the U.S. 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 (Text Box 1). The eventual extent of interest in carbon information may well depend on whether and how mandatory and incentive-based policies related to carbon management evolve. 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 U.S., 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 Climate Change Science Program (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 (U.S. Climate Change Science Program, 2006; Dilling, in press). There are relatively smaller investment research efforts at the Department of Energy (DOE) and the Department of Agriculture (USDA) under the CCSP[4] as well as significant technology efforts under 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.

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

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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.

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" (National Research Council, 2004). Moreover, they state that "managing risks 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" (National Research Council, 2004). Successful decision support, i.e., science that improves societal outcomes, requires knowledge of what decision-makers might use the information being generated, and what information would be most relevant to their decisions. Without such knowledge, information runs the risk of being "left on the loading-dock" and not used (Cash et al. 2006).

Two 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 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.

Improving the usefulness of carbon science in North America will require more explicit commitments by funding agencies, scientists, policy makers, and private sector managers to generate decision-relevant carbon cycle information. 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.

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; National Research Council, 1999; National Research Council, 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 U.S., 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).
- *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" (c.f. 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 component* (*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 U.S. 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/website/cquestwebsite/; 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 (Lemos and Morehouse, 2005).

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. And, 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 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, fishermen, 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 IPCC) to the Conference of the Parties, which focuses on setting policy.[5] The University of California Berkeley Digital Library Project Calflora project has explicitly designed their database on plants to support environmental planning (Van House *et al*., 2003).

Of course, other significant challenges exist to 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; that conflicts with pre-existing preferences, interests, or beliefs; or that conflicts with cognitive, organizational, sociological, or cultural norms (e.g., Douglas and Wildavsky, 1984; Lahsen, 1998; Yaniv, 2004; Lahsen, forthcoming). 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] http://unfccc.int/2860.php

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, the U.S. 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 U.S. 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" (National Research Council, 2004).

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" (National Research Council, 2004).

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 and 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.

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Sectors Expressing Interest and/or Participating in the SAP 2.2 Process. This list of sectors is neither exhaustive nor is it based on a statistically 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).

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, land-owners, 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).

Utilities and Industries: In the US, 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).

Transportation: Transportation accounts for approximately 37% of carbon emissions in the U.S., and about 22% worldwide. In transportation, 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)

Government: In the US, 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 (Government of Canada, 2005). The Mexican government appears to be particularly interested in locally-relevant research on natural and anthropogenic 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] (see Chapters 4 and 14).

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*., 2001).

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