United States Climate Change Science Program
Synthesis and Assessment Product 2.2
The First State of the Carbon Cycle Report (SOCCR): North American Carbon Budget and Implications for the Global Carbon Cycle

Executive Summary

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ABSTRACT

North America is currently a net source of carbon dioxide to the atmosphere, contributing to the global buildup of greenhouse gases in the atmosphere and associated changes in the earth's climate. In 2003, North America emitted nearly two billion metric tons of carbon to the atmosphere as carbon dioxide. North America's fossil fuel emissions in 2003 (1856 million metric tons of carbon ±10% with 95% certainty) were 27% of global emissions. Approximately 85% of those emissions were from the United States, 9% from Canada and 6% from Mexico. The conversion of fossil fuels to energy (primarily electricity) is the single largest contributor, accounting for approximately 42% of North American fossil emissions in 2003. Transportation is the second largest, accounting for 31% of total emissions.

There are also globally important carbon sinks in North America. In 2003, growing vegetation in North America removed approximately 530 million tons of carbon per year (± 50%) from the atmosphere and stored it as plant material and soil organic matter. This land sink is equivalent to approximately 30% of the fossil fuel emissions from North America. The imbalance between the fossil fuel source and the sink on land is a net release to the atmosphere of 1335 million metric tons of carbon per year (± 25%).

Approximately 50% of North America's terrestrial sink is due to the regrowth of forests in the United States on former agricultural land that was last cultivated decades ago, and on timber land recovering

from harvest. Other sinks are relatively small and not well quantified with uncertainties of 100% or more. The future of the North American terrestrial sink is also highly uncertain. The contribution of forest regrowth is expected to decline as the maturing forests grow more slowly and take up less carbon dioxide from the atmosphere. But, this expectation is surrounded by uncertainty because how regrowing forests and other sinks will respond to changes in climate and carbon dioxide concentration in the atmosphere is highly uncertain.

The large difference between current sources and sinks and the expectation that the difference could become larger if the growth of fossil fuel emissions continues and land sinks decline suggest that addressing imbalances in the North American carbon budget will likely require actions focused on reducing fossil fuel emissions. Options to enhance sinks (growing forests or sequestering carbon in agricultural soils) can contribute, but enhancing sinks alone is likely insufficient to deal with either the current or future imbalance. Options to reduce emissions include efficiency improvement, fuel switching, and technologies such as carbon capture and geological storage. Implementing these options will likely require both voluntary and policy-driven mechanisms at local, regional, national, and international levels. Meeting the demand for information by decision makers will likely require new modes of research characterized by close collaboration between scientists and carbon management stakeholders.

Synthesis and assessment of the North American carbon budget

Understanding the North American carbon budget, both sources and sinks, is critical to the United States Climate Change Science Program goal of providing the best possible scientific information to support public discussion, as well as government and private sector decision making, on key climate-related issues. In response, this Report provides a synthesis, integration and assessment of the current knowledge of the North American carbon budget and its context within the global carbon cycle. The Report is organized as a response to questions relevant to carbon management and to a broad range of stakeholders charged with understanding and managing energy and land use. The questions were identified through early and continuing dialogue with these stakeholders, including scientists, decision makers in the public and private sectors, including national and sub-national government; carbon-related industries, such as energy, transportation, agriculture, and forestry; and climate policy and carbon management interest groups.

The questions and the answers provided by this Report are summarized below. The reader is referred to the indicated chapters for further, more detailed, discussion. Unless otherwise referenced, all values, statements of findings and conclusions are taken from the chapters of this Report where the attribution and citation of the primary sources can be found.

What is the carbon cycle and why should we care?

The carbon cycle, described in Chapters 1 and 2, is the combination of many different physical, chemical and biological processes that transfer carbon between the major storage pools (known as reservoirs): the atmosphere, plants, soils, freshwater systems, oceans, and geological sediments. Hundreds of millions of years ago, and over millions of years, this carbon cycle was responsible for the formation of coal, petroleum, and natural gas, the fossil fuels that are the primary sources of energy for our modern societies.

Humans have altered the Earth's carbon budget. Today, the cycling of carbon among atmosphere, land, and freshwater and marine environments is in a rapid transition—an imbalance. Over tens of years, the combustion of fossil fuels is releasing into the atmosphere quantities of carbon that were accumulated in the earth system over millions of years. Furthermore, tropical forests that once held large quantities of carbon are being converted to agricultural lands, releasing additional carbon to the atmosphere as a result. Both the fossil-fuel and land-use related releases are *sources* of carbon to the atmosphere. The combined rate of release is far larger than can be balanced by the biological and geological processes that naturally remove carbon dioxide (CO_2) from the atmosphere and store it in terrestrial and marine environments as part of the earth's carbon cycle. These processes are known as *sinks*. Therefore, much of the carbon dioxide released through human activity has "piled up" in the atmosphere, resulting in a dramatic increase in the atmospheric concentration of carbon dioxide. The concentration increased by 31% between 1850 and 2003, and the present concentration is higher than at any time in the past 420,000 years. Because carbon dioxide is an important greenhouse gas, the imbalance between sources and sinks and the subsequent increase in concentration in the atmosphere is causing changes in the Earth's climate.

Furthermore, these trends in fossil fuel use and tropical deforestation are accelerating. The magnitude of the changes raises concerns about the future behavior of the carbon cycle. Will the carbon cycle continue to function as it has in recent history, or will a CO_2-caused warming result in a weakening of the ability of sinks to take up carbon dioxide, leading to further warming? Drought, for example, may reduce forest growth. Warming can release carbon stored in soil, and warming and drought may increase forest fires. Conversely, will elevated concentrations of carbon dioxide in the atmosphere stimulate plant growth as it is known to do in laboratory and field experiments and thus strengthen global or regional sinks?

The question is complicated because carbon dioxide is not the only substance in the atmosphere that affects the earth's surface temperature and climate. Other greenhouse gases include methane (CH_4), nitrous oxide, the halocarbons, and ozone, and all of these gases, together with water vapor, aerosols, solar radiation, and properties of the earth's surface, are involved in the evolution of climate change. Carbon dioxide, alone, is responsible for approximately 55-60% of the change in the Earth's radiation balance due to increases in well-mixed atmospheric greenhouse gases and methane, for about another

20% (values are for the late 1990s; with a relative uncertainty of 10%; IPCC, 2001). These two gases are the primary gases of the carbon cycle, with carbon dioxide being particularly important. Furthermore, the consequences of increasing atmospheric carbon dioxide extend beyond climate change alone. The accumulation of carbon in the oceans as a result of more than a century of fossil fuel use and deforestation has increased the acidity of the surface waters, with serious consequences for corals and other marine organisms that build their skeletons and shells from calcium carbonate.

Inevitably, the decision to influence or control atmospheric concentrations of carbon dioxide as a means to prevent, minimize, or forestall future climate change, or to avoid damage to marine ecosystems from ocean acidification, will require management of the carbon cycle. That management involves both reducing sources of carbon dioxide to the atmosphere and enhancing sinks for carbon on land or in the oceans. Strategies may involve both short- and long-term solutions. Short-term solutions may help to slow the rate at which carbon accumulates in the atmosphere while longer-term solutions are developed. In any case, formulation of options by decision makers and successful management of the earth’s carbon budget will require solid scientific understanding of the carbon cycle.

Understanding the current carbon cycle may not be enough, however. The concept of managing the carbon cycle carries with it the assumption that the carbon cycle will continue to operate as it has in recent centuries. A major concern is that the carbon cycle, itself, is vulnerable to land-use or climate change that could bring about additional releases of carbon to the atmosphere from either land or the oceans. Over recent decades both terrestrial ecosystems and the oceans have been natural sinks for carbon. If either, or both, of those sinks were to become sources, slowing or reversing the accumulation of carbon in the atmosphere could become much more difficult. Thus, understanding the current global carbon cycle is necessary for managing carbon, but is not sufficient. Projections of the future behavior of the carbon cycle in response to human activity and to climate and other environmental change are also important to understanding system vulnerabilities.

Perhaps even more importantly, effective management of the carbon cycle requires more than basic understanding of the current or future carbon cycle. It also requires cost-effective, feasible, and politically palatable options for carbon management. Just as carbon cycle knowledge must be assessed and evaluated, so must management options and tradeoffs. See Chapter 1 for further discussion of why the general public, as well as individuals and institutions interested in carbon management, should care about the carbon cycle.

How do North American carbon sources and sinks relate to the global carbon cycle?

In 2004 North America was responsible for approximately 25% of the carbon dioxide emissions produced globally by fossil fuel combustion (Chapter 2). The United States, the world's largest emitter of carbon dioxide, accounted for 86% of the North American total in 2004 (85% in 2003). In 2003, Canada accounted for 9%, and Mexico for 6%, of the total. North America contributed approximately 30% of cumulative carbon dioxide emissions globally from fossil-fuel combustion (and cement manufacturing) since 1750 (through 2002). Among all countries, the United States, Canada, and Mexico ranked, respectively, as the first, seventh, and eleventh largest emitters of carbon dioxide from fossil fuels in 2003 (Marland *et al*., 2006). The United States ranked eleventh in per capita emissions (5.43 tons carbon per year) in 2003; Canada ranked thirteenth (4.88 tons carbon per year) and Mexico eighty-ninth (1.10 tons carbon per year). Per capita emissions of the United States and Canada were, respectively, 4.8 and 4.3 times the global per capita emissions of 1.14 tons carbon per year. Mexico's per capita emissions were slightly below the global value. Combined, these three countries contributed more than a quarter (27%) of the world's entire fossil-fuel carbon dioxide emissions in 2002 and almost one third (32%) of the cumulative global fossil-fuel carbon dioxide emissions between 1751 and 2002. Emissions from parts of Asia are increasing at a growing rate and may surpass those of North America in the near future, but North America is incontrovertibly a major source of atmospheric carbon dioxide, historically, at present, and in the immediate future.

The contribution of North American carbon sinks to the global carbon budget is less clear. The *global* terrestrial sink is quite uncertain, averaging somewhere in the range of 0 to 3800 million tons of carbon per year during the 1980s, and in the range of 1000 to 3600 million tons of carbon per year in the 1990s (IPCC, 2000). This report estimates a North American sink of approximately 500 million tons of carbon per year for 2003, with 95% certainty that the actual value is within plus or minus 50% of that estimate, or between 250 and 750 million tons carbon per year (Chapter 3) (see the Text Box on *Treatment of Uncertainty*). Assuming a global terrestrial sink of approximately two billion tons of carbon per year (as inferred by the atmospheric analyses for the 1990s), the North American terrestrial sink reported here of approximately 500 million tons of carbon per year suggests that the North American sink is perhaps 25% of the global sink. In contrast, previous analyses using global models of carbon dioxide transport in the atmosphere estimate a North American sink for 1991-2000 of approximately one billion tons of carbon per year, or approximately 50% of a global sink of roughly two billion tons of carbon per year (see Chapter 2). The North American sink estimate of this Report is derived from studies using ground-based inventories, and the difference between estimates is likely influenced by the methodology employed and the period of the analysis (see Chapters 2 and 3).

TEXT BOX on *Treatment of Uncertainty* goes here

The global terrestrial sink is predominantly in northern lands, most likely as a consequence of forest regrowing on abandoned agricultural land in northern temperate regions (e.g., the eastern United States) and patterns of forest fire and recovery in the boreal forests of Canada and Eurasia. The sink north of 30° N alone is estimated to be 600 to 2300 million tons of carbon per year for the 1980s (IPCC, 2001). Thus, the sink of approximately 500 million tons of carbon per year in North America is consistent with the fraction of northern land area in North America (37%), as opposed to Eurasia (63%). Rates of forest clearing in the tropics, including those of Mexico, currently exceed rates of recovery, and thus tropical regions dominated by rainforests or other forest types are currently a source of carbon to the atmosphere.

It is clear that the global carbon cycle of the 21st century will continue to be influenced by large fossil-fuel emissions from North America, and that the North American carbon budget will continue to be dominated by the fossil-fuel sources. The future trajectory of carbon sinks in North America, and their contribution to the global terrestrial sink is less certain, in part because the role of regrowing forests is likely to decline as the forests mature, and in part because the response of forests and other ecosystems to future climate change and increases in atmospheric carbon dioxide concentrations is uncertain. The variation among model projections and scenarios of where and how future climate will change contribute to that uncertainty. Additionally, response to a particular future change will likely vary among ecosystems and the response will depend on a variety of incompletely understood environmental factors.

What are the primary carbon sources and sinks in North America, and how and why are they changing?

The Sources

The primary source of human-caused carbon emissions in North America that contributes to the increase of carbon dioxide in the atmosphere is the release of carbon dioxide during the combustion of fossil fuels (Figure ES-1) (Chapter 3). Fossil fuel carbon emissions in the United States, Canada and Mexico totaled approximately 1900 million tons of carbon in 2003 (with 95% confidence that the actual value lies within 10% of that estimate[1]) and have increased at an average rate of approximately 1% per year for the last 30 years. The United States was responsible for approximately 85% of North America's fossil fuel emissions in 2003, Canada for 9% and Mexico 6% (Table ES-1). The overall 1% growth in

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[1] See the Text Box on *Treatment of Uncertainty* for a discussion of numerical data and estimates.

United States emissions masks faster than 1% growth in some sectors (e.g., transportation) and slower growth in others (e.g., increased manufacturing energy efficiency).

Figure ES-1. North American carbon sources and sinks (million tons of carbon per year**) in 2003.** Height of a bar indicates a best estimate for net carbon exchange between the atmosphere and the indicated element of the North American carbon budget. Sources add carbon dioxide to the atmosphere; sinks remove it. Error bars indicate the uncertainty in that estimate, and define the range of values that include the actual value with 95% certainty. See Chapter 3 and Chapters 6-15 of this report for details and discussion of these sources and sinks.

Table ES-1. North American annual net carbon emissions (source = positive) or uptake (land sink = negative) (million tons of carbon per year) by country. See Table 3-1, Chapter 3 for references to sources of data.

Total United States emissions have grown at close to the North American average rate of about 1.0% per year over the past 30 years, but United States per capita emissions have been roughly constant, while the carbon intensity (carbon emitted/dollar of real [inflation adjusted] GDP) of the United States economy has decreased at a rate of about 2% per year (Chapter 3). The decline in the carbon intensity of the United States' economy was caused both by increased energy efficiency, particularly in the manufacturing sector, and structural changes in the economy with growing contributions from sectors such as services with lower energy consumption and carbon intensity. The service sector is likely to continue to grow. Accordingly, carbon emissions will likely continue to grow more slowly than GDP (see Chapter 3).

The extraction of fossil-fuels and other primary energy sources and their conversion to energy commodities and services, including electricity generation, is the single largest contributor to the North American fossil-fuel source, accounting for approximately 42% of North American fossil emissions in 2003 (Chapter 6). Electricity generation is responsible for the largest share of those emissions: approximately 94% in the United Sates in 2004, 65% in Canada in 2003, and 67% in Mexico in 1998. Again, United States emissions dominate. United States emissions from electricity generation are approximately 17 times larger than those of Canada and 23 times those of Mexico, reflecting in part the relatively greater population of the United States in both cases and its much higher level of development than Mexico. On a per capita basis, the emissions from electricity generation are 2.14 tons of carbon for the United States in 2004, 1.15 tons of carbon for Canada in 2003, and 0.28 tons of carbon for Mexico in 1998 (note these are the latest years for which data are available).

More than half of electricity produced in North America (67% in the United States) is consumed in buildings, making that single use one of the largest factors in North American emissions (Chapter 9). In fact, the carbon dioxide emissions from United States buildings alone were greater than total carbon dioxide emissions of any country in the world, except China. Energy use in buildings in the United States and Canada (including the use of natural gas, wood, and other fuels as well as electricity) has increased by 30% since 1990, corresponding to an annual growth rate of 2.1%. In the United States, the major drivers of energy consumption in the buildings sector are growth in commercial floor space and increase in the size of the average home. Carbon emissions from buildings are expected to grow with population and income. Furthermore, the shift from family to single-occupant households means that the number of households will increase faster than population growth—each household with its own heating and cooling systems and electrical appliances. Certain electrical appliances (such as air-conditioning equipment) once considered a luxury are now becoming commonplace. Technology- and market-driven improvements in the efficiency of appliances are expected to continue, but the improvements will probably not be sufficient to curtail emissions growth in the buildings sector without government intervention.

The transportation sector of North America accounted for 31% of total North American emissions in 2003, most (87%) of it from the United States (Chapter 7). The growth in transportation and associated carbon dioxide emissions has been steady during the past forty years and has been most rapid in Mexico, the country most dependent upon road transport. The growth of transportation is driven by population, per capita income, and economic output, and energy use in transportation is expected to increase by 46% in North America between 2003 and 2025. If the mix of fuels is assumed to remain the same, carbon dioxide emissions would increase from 587 million tons of carbon in 2003 to 859 million tons of carbon in 2025.

Emissions from North American industry (not including fossil fuel mining and processing or electricity generation) are a relatively small (12%) and declining component of North America’s emissions (Chapter 8). Emissions decreased nearly 11% between 1990 and 2002, while energy consumption in the United States and Canada increased by 8-10% during that period. In both countries, a shift in production toward less energy-intensive industries and dissemination of more energy efficient equipment has kept the rate of growth in energy demand lower than the rate of growth of industrial GDP. Emission reductions in industry have also resulted from the voluntary, proactive initiatives of both individual corporations and trade associations in response to climate change issues (see Chapter 4).

The remaining portion (approximately 15%) of North American fossil-fuel emissions includes those from other sectors. This includes natural gas and other non-electrical fossil energy used in residential and commercial buildings and fuels used in agriculture.

The Sinks

Approximately 30% of North American fossil fuel emissions are offset by a sink of approximately 530 million tons of carbon per year. The total sink is a combination of many factors, including forest regrowth, fire suppression, and agricultural soil conservation (Figure ES-1) (Chapter 3, Part III: Chapters 10-15). The sink is currently about 500 million tons of carbon per year in the United States and approximately 80 million tons of carbon per year in Canada. Mexican ecosystems are a net source of about 50 million tons of carbon per year, mostly as a consequence of ongoing deforestation. The coastal ocean surrounding North America is perhaps an additional small net source of carbon to the atmosphere of approximately 20 million tons of carbon per year. The coastal ocean is, however, highly variable, and that number is highly uncertain with a variability (standard deviation) of greater than 100%. North America's coastal waters could be a small sink and in some places are. How much the coastal carbon exchange with the atmosphere is influenced by humans is also unknown.

The primary carbon sink in North America (approximately 50%) is in the forests of the United States and Canada (Figure ES-1). These forests are still growing (accumulating carbon) after their re-colonization of farmland 100 or more years ago. Forest regrowth takes carbon out of the atmosphere and stores most of it in aboveground vegetation (wood), with as much as a third of it in soils. The suppression of forest fires also increases a net accumulation of carbon in forests. As the recovering forests mature, however, the rate of net carbon uptake (the sink) declines. In Canada, the estimated forest sink declined by nearly a third between 1990 and 2004, but with high year-to year variability. Over that period, the annual changes in above ground carbon stored in managed Canadian forests varied from between a sink of approximately 50 million tons of carbon per year to a source of approximately 40 million tons of carbon per year. Years when the forests were a source were generally years with high forest fire activity.

Woody encroachment, the invasion of woody plants into grasslands or of trees into shrublands, is a potentially large, but highly uncertain carbon sink. 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 levels, and this reduction favors shrubs and trees in competition with grasses. The sink may be as large as 20% of the North American sink, but it may also be negligible. The uncertainty of this estimate is greater than 100%. Woody encroachment might actually be a *source*, maybe even a relatively large one. The state of the science is such that we simply don't know (see Chapter 3 and the Overview of Part III).

Wood products are thought to account for about 13% of the total North American sink. The uncertainty in this sink is ±50%. Wood products are a sink because they are increasing, both in use (e.g., furniture, house frames, etc.) and in landfills. The wetland sink, about 9% of the North American sink but with an uncertainty of greater than 100%, is in both the peats of Canada's extensive frozen and unfrozen wetlands and the mineral soils of Canadian and United States wetlands. Drainage of peatlands in the United States has released carbon to the atmosphere, and the very large volume of carbon in North American wetlands (the single largest carbon reservoir of any North American ecosystem) is vulnerable to release in response to both climate change and the further drainage of wetlands for development. Either change might shift the current modest sink to a potentially large source, although many aspects of wetlands and their future behavior are poorly known.

Two processes determine the carbon balance of agricultural lands: management and changes in environmental factors. The effects of management (e.g., cultivation, conservation tillage) are reasonably well known and have been responsible for historic losses of carbon in Canada and the United States (and current losses in Mexico), albeit with some increased carbon uptake and storage in recent years. Agricultural lands in North America are nearly neutral with respect to carbon, with mineral soils absorbing carbon and organic soils releasing it. The balance of these sinks and sources is a net sink of 10 ± 5 million tons of carbon per year (Fig. ES-1). The effects of climate on this balance are not well known.

Soil erosion leads to the accumulation of carbon containing sediments in streams, rivers and lakes (both natural and man-made). This represents a carbon sink, estimated at approximately 25 million tons of carbon per year for the United States. We know of no similar analysis for Canada or Mexico. The result is a highly uncertain estimate for North America known to no better than the estimate for the United States alone, plus or minus more than 100%.

The density and development patterns of human settlements are drivers of fossil-fuel emissions, especially in the important residential and transportation sectors. Conversion of agricultural and wildlands to cities and other human settlements reduces carbon stocks, while the growth of urban and suburban trees increases them. However, the rates of carbon uptake and storage in the vegetation and soils of settlements, while poorly quantified, are probably relatively small, certainly in comparison to fossil fuel emissions from these areas. Thus, settlements in North America are almost certainly a net source of atmospheric carbon.

What are the direct, non-climatic effects of increasing atmospheric carbon dioxide or other changes in the carbon cycle on the land and oceans of North America?

The potential impacts of increasing concentrations of atmospheric carbon dioxide (and other greenhouse gases) on the earth's climate are well documented (IPCC, 2001) and are the dominant reason for societal interest in the carbon cycle. However, the consequences of a carbon cycle imbalance and the buildup of carbon dioxide in the atmosphere extend beyond climate change alone. Ocean acidification and "CO_2 fertilization" of land plants are foremost among these direct, non-climatic effects.

The uptake of carbon by the world's oceans as a result of human activity over the last century has made them more acidic (see Chapters 1 and 2). This acidification negatively impacts corals and other marine organisms that build their skeletons and shells from calcium carbonate. Future changes could dramatically alter the composition of ocean ecosystems of North America and elsewhere, possibly eliminating coral reefs by 2100.

Rates of photosynthesis of many plant species often increase in response to elevated concentrations of carbon dioxide, thus potentially increasing plant growth and even agricultural crop yields in the future (Chapters 2, 3, 10-13). There is, however, continuing scientific debate about whether such "CO_2 fertilization" will continue into the future with prolonged exposure to elevated carbon dioxide, and whether the fertilization of photosynthesis will translate into increased plant growth and net uptake and storage of carbon by terrestrial ecosystems. Recent studies provide many conflicting results. Experimental treatment with elevated carbon dioxide can lead to consistent increases in plant growth. On the other hand, it can also have little effect on plant growth, with an initial stimulation of photosynthesis but limited long-term effects on carbon accumulation in the plants. Moreover, it is unclear how plants and ecosystem might respond simultaneously to both "CO_2 fertilization" and climate change. While there is some experimental evidence that plants may use less water when exposed to elevated carbon dioxide, extended deep drought or other unfavorable climatic conditions could reduce the positive effects of elevated carbon dioxide on plant growth. Thus, it is far from clear that elevated concentrations of atmospheric carbon dioxide have led to terrestrial carbon uptake and storage or will do so over large areas in the future. Moreover, elevated carbon dioxide is known to increase methane emissions from wetlands, further increasing the uncertainty in how plant response to elevated carbon dioxide will affect the global atmosphere and climate.

The carbon cycle also intersects with a number of critical earth system processes, including the cycling of both water and nitrogen. Virtually any change in the lands or waters of North America as part of purposeful carbon management will consequently affect these other processes and cycles. Some interactions may be beneficial. For example, an increase in organic carbon in soils is likely to increase the availability of nitrogen for plant growth and enhance the water-holding capacity of the soil. Other interactions, such as nutrient limitation, fire, insect attack, increased respiration from warming, may be detrimental. However, very little is known about the complex web of interactions between carbon and other systems at continental scales, or the effect of management on these interactions.

What potential management options in North America could significantly affect the North American and global carbon cycles (e.g., North American sinks and global atmospheric carbon dioxide concentrations)?

Addressing imbalances in the North American and global carbon cycles requires options focused on reducing carbon emissions (Chapter 4). Options focused on enhancing carbon sinks in soils and vegetation can contribute as well, but their potential is far from sufficient to deal with the magnitude of current imbalances.

Currently, options for reducing carbon emissions include:

- Reducing emissions from the transportation sector through efficiency improvement, higher prices for carbon-based fuels, liquid fuels derived from vegetation (ethanol from corn or other biomass feedstock, for example), and in the longer run (after 2025), hydrogen generated from non-fossil sources of energy;
- Reducing the carbon emissions associated with energy use in buildings through efficiency improvements and energy-saving passive design measures;
- Reducing emissions from the industrial sector through efficiency improvement, fuel-switching, and innovative process designs; and
- Reducing emissions from energy extraction and conversion through efficiency improvement, fuel-switching, technological change (including carbon sequestration and capture and storage) and reduced demands due to increased end-use efficiency.
- Capturing the carbon dioxide emitted from fossil-fired generating units and injecting it into a suitable geological formation or deep in the sea for long-term storage (carbon capture and storage).

In many cases, significant progress with such options would require a combination of technology research and development, policy interventions, and information and education programs.

Opinions differ about the relative mitigation impact of emission reduction versus carbon sequestration. Assumptions about the cost of mitigation and the policy instruments used to promote mitigation significantly affect assessments of mitigation potential. For example, appropriately designed carbon emission cap and trading policies could achieve a given level of carbon emissions reduction at lower cost than some other policy instruments by providing incentives to use the least-cost combination of mitigation/sequestration alternatives.

However, the evaluation of any policy instrument needs to consider technical, institutional and socioeconomic constraints that would affect its implementation, such as the ability of sources to monitor their actual emissions, the constitutional authority of national and/or provincial/state governments to impose emissions taxes, regulate emissions and/or regulate efficiency standards. Also, practically every policy (except cost-saving energy conservation 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. These costs must be weighed against the benefits (or avoided costs) of reducing carbon emissions. In addition to the standard reduction in damages noted above, many options and measures that reduce emissions and increase sequestration also have significant *co-benefits* in terms of economic efficiency (where market failures are being corrected, as in many cases of energy conservation), environmental management, and energy security.

The design of carbon management systems must also consider unintended consequences involving other greenhouse gases. For instance, carbon sequestration strategies such as reduced tillage can increase emissions of methane and nitrous oxide, which are also greenhouse gases. Strategies for dealing with climate change will have to consider these other gases as well as other components of the climate systems, such as small airborne particles and the physical aspects of plant communities.

Direct reductions of carbon emissions from fossil fuel use are considered ‘permanent’ reductions, while carbon sequestration in plants or soils is a ‘non-permanent’ reduction, in that carbon stored through conservation practices could potentially be re-emitted if management practices revert back to the previous state or otherwise change. This *permanence* issue applies to all forms of carbon sinks. For example, the carbon sink associated with forest regrowth could be slowed or reversed from sink to source if the forests are burnt in wildfires or forest harvest and management practices change.

In addition, a given change in land management (e.g., tillage reduction, pasture improvement, afforestation) will stimulate carbon storage for only a finite period of time. Over time, as the processes of carbon gain and loss from vegetation and soil comes into a new balance with the change in land management, carbon storage will tend to level off at a new maximum, after which there is no further accumulation (sequestration) of carbon. For example, following changes in tillage to promote carbon absorption in agricultural soils (see Chapter 10) the amount of carbon in the soil will tend to reach a new constant level after 15–30 years. The sink declines, then disappears, or nearly so, as the amount of carbon being added to the soil is balanced by losses. The same pattern is observed as forests recover from fire, harvest or other disturbance, or as forests regrowing on abandoned farmland become more mature (see Chapters 3 and 11).

Another issue surrounding carbon uptake and storage is *leakage*, whereby mitigation actions in one area (e.g., geographic region, production system) stimulate additional emissions elsewhere. For storage of carbon in forests, leakage is a major concern; reducing harvest rates in one area, for example, can stimulate increased cutting and reduction in stored carbon in other areas. Leakage may be of minor concern for agricultural carbon storage, since most practices would have little or no effect on the supply and demand of agricultural commodities.

Options and measures can be implemented in a variety of ways at a variety of scales, not only at international or national levels. For example, a number of municipalities, state governments, and private firms in North America have made commitments to voluntary greenhouse gas emission reductions. For cities, one focus has been the Cities for Climate Protection program of International Governments for Local Sustainability (formerly ICLEI). For some states and provinces, the Regional Greenhouse Gas (Cap and Trade) Initiative is nearing implementation. For industry, one focus has been membership in the Pew Center and in the Environmental Protection Agency (EPA) Climate Leaders Program.

How can we improve the usefulness of carbon science for decision making?

Effective carbon management requires that relevant, appropriate science be communicated to the wide variety of people whose decisions affect carbon cycling (Chapter 5). Because the field is relatively new and the demand for policy-relevant information has been limited, carbon cycle science has rarely been organized or conducted to inform carbon management. To generate information that can systematically inform carbon management decisions, scientists and decision makers need to clarify what information would be most relevant in specific sectors and arenas for carbon management, adjust research priorities as necessary, and develop mechanisms that enhance the credibility and legitimacy of the information being generated.

In the United States, the Federal carbon science enterprise does not yet have many mechanisms to assess emerging demands for carbon information across scales and sectors. Federally funded carbon science has focused predominantly on basic research to reduce uncertainties about the carbon cycle. Initiatives are now underway to promote coordinated, interdisciplinary research that is strategically prioritized to address societal needs. The need for this type of research is increasing. Interest in carbon management across sectors suggests that there may be substantial demand for information in the energy, transportation, agriculture, forestry and industrial sectors, at scales ranging from local to global.

To ensure that carbon science is as useful as possible for decision making, carbon scientists and carbon managers need to create new forums and institutions for communication and coordination. Research suggests that in order to make a significant contribution to management, scientific and technical information intended for decision making must be perceived not only as credible (worth believing), but also as salient (relevant to decision making on high priority issues) and legitimate (conducted in a way that stakeholders believe is fair, unbiased and respectful of divergent views and interests). To generate information that meets these tests, carbon stakeholders and scientists need to collaborate to develop research questions, design research strategies, and review, interpret and disseminate results. Transparency and balanced participation are important for guarding against politicization and enhancing usability.

To make carbon cycle science more useful to decision makers in the United States and elsewhere in North America, leaders in the carbon science community might consider the following steps:

- Identify specific categories of decision makers for whom carbon cycle science is likely to be salient, focusing on policy makers and private sector managers in carbon-intensive sectors (energy, transport, manufacturing, agriculture and forestry);

- Identify and evaluate existing information about carbon impacts of decisions and actions in these arenas, and assess the need and demand for additional information. In some cases, demand may need to be nurtured and fostered through a two-way interactive process;
- Encourage scientists and research programs to experiment with new and different ways of making carbon cycle science more salient, credible, and legitimate to carbon managers;
- Involve not just physical or biological disciplines in scientific efforts to produce useable science, but also social scientists, economists, and communication experts; and
- Consider initiating participatory pilot research projects and identifying existing "boundary organizations" (or establishing new ones) to bridge carbon management and carbon science.

What additional knowledge is needed for effective carbon management?

Scientists and carbon managers need to improve their joint understanding of the top priority questions facing carbon-related decision-making. Priority needs specific to individual ecosystem or sectors are described in Chapters 6-15 of this report. To further prioritize those needs across disciplines and sectors, scientists need to collaborate more effectively with decision makers in undertaking research and interpreting results in order to answer those questions. To improve this understanding, more deliberative processes of consultation with potential carbon managers at all scales can be initiated at various stages of the research process. This might include workshops, focus groups, working panels, and citizen advisory groups. Research on the effective production of science that can be used for decision making suggests that ongoing, iterative processes that involve decision makers are more effective than those that do not (see Chapter 5).

In the light of changing views on the impacts of CO_2 released to the atmosphere, research and development will likely focus on the extraction of energy while preventing CO_2 release. Fossil fuels might well remain economically competitive and socially desirable as a source of energy in some circumstances, even when one includes the extra cost of capturing the CO_2 and preventing its atmospheric release when converting these fuels into non-carbon secondary forms of energy like electricity, hydrogen or heat. Research and development needs in the energy and conversion arena include clarifying potentials for carbon capture and storage, exploring how to make renewable energy affordable at large scales of deployment, examining societal concerns about nuclear energy, and learning more about policy options for distributed energy and energy transitions. There is also need for better understanding of the public acceptability of policy incentives for reducing dependence on carbon intensive energy sources.

In the transportation sector, improved data on Mexican greenhouse gas emissions and trends is needed, as well as the potential for mitigating transportation-related emissions in North America and advances in transportation mitigation technologies and policies. In the industry and waste management sectors, work on materials substitution and energy efficient technologies in production processes holds promise for greater emissions reductions. Needs for the building sector include further understanding the total societal costs of CO_2 as an externality of buildings costs, economic and market analyses of various reduced emission features at various time scales of availability, and construction of cost curves for emission reduction options.

Turning to the ecosystem arena, in agricultural and grazing land sectors inventories still carry a great deal of uncertainty, especially in the arena of woody encroachment. If such inventories are to be the basis for future decision making, reducing such uncertainties may be a useful investment. Quantitative estimates of land use change and the impact of various management practices are also highly uncertain, as are the interactions among carbon dioxide, methane, and nitrous oxide as greenhouse gas emissions. If carbon accounting becomes a critical feature of carbon management, improved data are needed on the relationship of forest management practices to carbon storage, as well as inexpensive tools and techniques for monitoring. An assessment of agroforestry practices in Mexico as well as in temperate landscapes would also be helpful. Importantly, there is a need for multi-criteria analysis of various uses of landscapes—tradeoffs between carbon storage and other uses of the land must be considered. If markets emerge more fully for trading carbon credits, the development of such decision support tools will likely be encouraged.

Soils in the permafrost region store vast amounts of carbon, but there is little certainty about how these soils will respond to changes brought about by climate. While these regions are likely not subject to management options, improved information on carbon storage and the trajectory of these reservoirs may provide additional insight into the likelihood of release of large amounts of carbon to the atmosphere that may affect global decision making. Similarly, there is great uncertainty in the response of the carbon pools of wetlands to climate changes, and very little data on freshwater mineral soils and estuarine carbon both in Canada and Mexico.

With respect to human settlements, additional studies of the carbon balance of settlements of varying densities, geographical location, and patterns of development are needed to quantify the potential impacts of various policy and planning alternatives on net greenhouse gas emissions. Finally, in the coastal regions, additional information on carbon fluxes will help to constrain continental carbon balance estimates should information on that scale become useful for decision making. Research on ocean carbon uptake and storage is also needed in order to fully inform decision making on options for carbon management.

With respect to carbon management, there is a need for more insight into how incentives to reduce emissions affect the behavior of households and businesses, the influence of reducing uncertainty on the willingness of decision makers to make commitments, the affect of increased R& D spending on technological innovation, the socioeconomic distribution of mitigation/sequestration costs and benefits, and the manner in which mitigation costs and policy instrument design affect the macroeconomy. Improvements in decision analysis in the face of irreducible uncertainty would be helpful as well.

EXECUTIVE SUMMARY REFERENCES

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Marland, G., T.A. Boden, and R.J. Andres, 2006: *Global, Regional, and National Fossil Fuel* CO_2 *Emissions. In Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.

[START OF TEXT BOX]

Treatment of Uncertainty

Sources of uncertainty vary widely across the many sectors and elements of the North American carbon cycle. The attention to uncertainty and the methods for dealing with uncertainty also vary across the disciplines that study these elements and across individual studies and publications. There is no single applicable quantitative method for integrating these variable sources, methods, and characterizations.

To provide for synthesis across and comparability among carbon cycle elements, the following convention has been adopted for characterizing uncertainty in the Report's synthetic findings and results (for example, in the synthesized carbon budget for North America of Chapter 3 and in the *Executive Summary*). Uncertainty is characterized using five categories:

(1) ***** = 95% certain that the actual value is within 10% of the estimate reported,
(2) **** = 95% certain that the estimate is within 25%,
(3) *** = 95% certain that the estimate is within 50%,
(4) ** = 95% certain that the estimate is within 100%, and
(5) * = uncertainty > 100%.

Unless otherwise noted, values presented as "y ± x%" should be interpreted to mean that the authors are 95% certain the actual value is between y – x% and y + x%. Where appropriate, the absolute range is sometimes reported rather than the relative range: y ± z, where z = y × x% ÷ 100. The system of asterisks is used as shorthand for the categories in tables and text.

These are informed categorizations. They reflect expert judgment, using all known published descriptions of uncertainty surrounding the "best available" or "most likely" estimate. The 95% boundary was chosen to communicate the high degree of certainty that the actual value was in the reported range and the low likelihood (1/20) that it was outside that range. This characterization is not, however, a statistical property of the estimate, and should not be confused with statistically defined 95% confidence intervals.

The authors of this Report have used this system for categorizing uncertainty only where they have synthesized diverse published information and compared across this diversity. When citing an existing published estimate, authors were encouraged to include the characterizations of uncertainty reported by those publications (e.g., ranges, standard error, or confidence intervals). There are circumstances in which no characterization of the uncertainty of data or information is shown, such as when a number is taken from a published source that itself did not include a characterization of uncertainty. In these cases, the authors have not provided a characterization of uncertainty, and the reader should assume that no characterization of uncertainty was available to the authors. Additional discussion of sources of uncertainty and their treatment in this Report can be found in the *Preface* under "The Treatment of Uncertainty in this Report."

[END OF TEXT BOX]

Table ES-1. North American annual net carbon emissions (source = positive) or uptake (land sink = negative) (million tons carbon per year) by country. See Table 3-1, Chapter 3 for references to sources of data.

Source (positive) or Sink (negative)	United States	Canada	Mexico	North America
Fossil source (positive)				
Fossil fuel (oil, gas, coal)	1582***** (681, 328, 573)	164***** (75, 48, 40)	110***** (71, 29, 11)	1856***** (828, 405, 624)
Nonfossil carbon sink (negative) or source (positive)				
Forest	–259***	–47***	+52**	–254***
Wood products	–57***	–11 ***	ND	–68***
Woody encroachment	–120*	ND	ND	–120*
Agricultural soils	–8***	–2 ***	ND	–10 ***
Wetlands	–23*	–23*	–4*	–49*
Rivers and lakes	–25 **	ND	ND	–25*
Coastal oceans [a]				
Total carbon source or sink	–492***	–83**	48*	–526***
Net carbon source (positive)	1090****	81***	158***	1330****

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] Coastal waters within 100 km of the North American coastline, defined by the region in which the surface water concentration of carbon dioxide is influenced by coastal processes, may be a source of 19 million tons of carbon per year but with 95% confidence bounds of > 100% (i.e., they may be a small sink). See discussion of coastal ocean sources and sinks in Chapters 3 and 15, and their distribution by ocean region rather than country in Chapter 15.

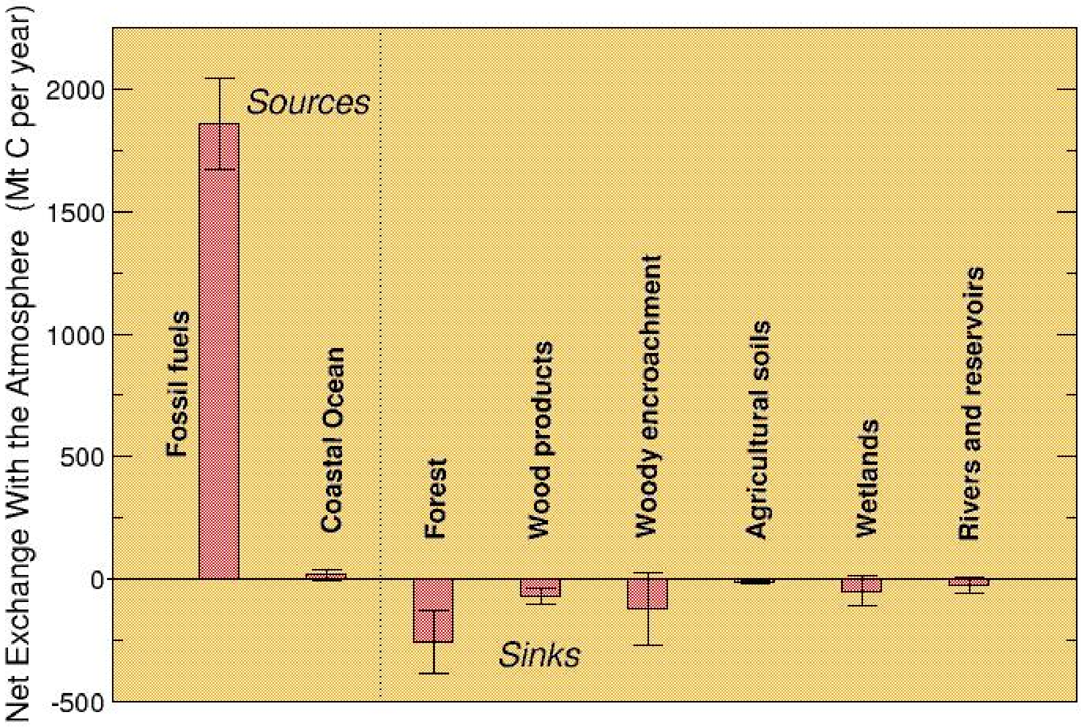

Figure ES-1. North American carbon sources and sinks (million tons carbon per year) circa 2003. Height of a bar indicates a best estimate for net carbon exchange between the atmosphere and the indicated element of the North American carbon budget. Sources add carbon dioxide to the atmosphere; sinks remove it. Error bars indicate the uncertainty in that estimate, and define the range of values that include the actual value with 95% certainty. See Chapter 3 and Chapters 6-15 of this report for details and discussion of these sources and sinks.