U.S. 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

Lead Authors: SOCCR Coordinating Team

Coordinating Team Members: Lisa Dilling[1], Anthony King[2], David Fairman[3], Richard Houghton[4], Gregg Marland[2], Adam Rose[5], Thomas Wilbanks[2], and Gregory Zimmerman[2]

[1]University of Colorado, [2]Oak Ridge National Laboratory, [3]Consensus Building Institute, Inc., [4]Woods Hole Research Center, [5]The Pennsylvania State University

The Earth's carbon budget is in imbalance. Beginning with the Industrial Revolution in the 18th century, but most dramatically since World War II, the human use of coal, petroleum, and natural gas has transferred large amounts of carbon from geological reservoirs to the atmosphere, primarily as the combustion product carbon dioxide (CO_2). Clearing of forests and plowing of grasslands for agriculture has also transferred carbon from plants and soils to the atmosphere as CO_2. The combined rate of transfer is far larger than can be balanced by the biological and geological processes which naturally remove CO_2 from the atmosphere and store the carbon in various terrestrial and marine reservoirs as part of the earth's carbon cycle. The result is a "piling up" of CO_2 in the atmosphere, and a dramatic increase in atmospheric CO_2 concentration. The atmospheric concentration of carbon dioxide has increased by 31% since 1750, and the present concentration is now higher than at any time in the past 420,000 years and perhaps the past 20 million years. Because CO_2 is an important greenhouse gas, this imbalance and buildup in the atmosphere has consequences for climate and climate change.

North America is a major contributor to this imbalance. Among all countries, the United States, Canada, and Mexico ranked, respectively, as the first, eighth, and eleventh largest emitters of CO_2 from fossil fuels in 2002. Combined, these three countries contributed almost a third (32%) of the world's entire fossil fuel emissions in 2002 and more than quarter (27%) in 2003. North America is incontrovertibly a major source of atmospheric CO_2.

North America may also be an important sink. Many lines of scientific evidence point to the vegetation and soils of the Northern Hemisphere as a net sink for atmospheric carbon, removing CO_2 from the atmosphere and to some degree mitigating fossil-fuel sources. The contribution of North America to that sink is, however, highly uncertain. The mechanisms that might be responsible for a North American sink, including forest regrowth and sequestration in agricultural soils, are reasonably well known. However, their relative contributions, their magnitudes, and their future fates are highly uncertain.

Understanding the North American carbon budget, both sources and sinks, is critical to the U.S. 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 about the North American carbon budget relevant to carbon management policy options and a broad range of stakeholder groups interested in knowledge of carbon cycling in North America and of how such knowledge might be used to influence or make decisions. The questions were identified through early and continuing dialogue with these stakeholder groups, including scientists, decision makers in the public sector (Federal, State, and local governments), the private sector (carbon-related industry, including energy, transportation, agriculture, and forestry sectors; and climate policy and carbon management interest groups), the international community, and the general public.

The questions and the answers provided by this Report are summarized below.

What is the carbon cycle and why should we care?

The carbon cycle is the combination of many different physical, chemical and biological processes that transfer carbon between storage pools or reservoirs in the atmosphere, plants, soils, freshwater systems, ocean and geological sediments. We are familiar with the cycling of water in precipitation, runoff, stream flow, and evaporation. Water delivered from the atmosphere in rain and snow evaporates from land, freshwater rivers and lakes, and the ocean, and condenses in the atmosphere to form clouds. These clouds generate rain or snow, and the cycle begins anew. Similarly, carbon cycles through the atmosphere, land and water, and over long periods of time, through the earth's rocky crust itself.

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 source of energy for our modern, post-industrial societies. Today, the cycling of carbon among atmosphere, land, freshwater and marine reservoirs over periods of years and decades determines the balance of the carbon budget observed at any particular time: how much carbon is stored in a reservoir, how much is coming in, how much is going out, and how fast the carbon pool is changing. Currently the global carbon budget is in imbalance, with carbon building up in the atmosphere as carbon dioxide, and human use of coal, petroleum and natural gas to fuel economies is responsible.

If vast quantities of water had been trapped underground for millions of years and then, in recent decades, 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. This has not happened for water, but it has happened for carbon. The 19th and especially 20th centuries saw a dramatic rise in the combustion of "fossil fuels," releasing into the atmosphere over *decades* quantities of carbon that had been stored in the earth system over thousands of *millennia*. During this same time, forests that had once absorbed very large quantities of carbon dioxide were being converted to agricultural cropland with carbon released to the atmosphere during clearing.

It is not surprising, then, that concentrations of carbon dioxide and other carbon compounds in the earth's atmosphere, such as methane, are increasing. This facts, together with patterns of human activity that are likely to continue trends in fossil fuel use and deforestation, raise concerns about imbalances in the carbon cycle and their implications.

Climate change is an obvious concern. Atmospheric carbon dioxide is the largest single forcing agent of climate change. However, the consequences of increasing atmospheric carbon dioxide extend beyond climate change alone. It is increasingly evident that elevated atmospheric carbon dioxide concentrations are responsible for increased acidification of the surface ocean, with potentially dire future consequences for corals and other marine organisms that build their skeletons and shells from calcium carbonate. Ocean acidification is a powerful reason in addition to that of climate change to care about the carbon cycle and the accumulation of carbon dioxide in the atmosphere.

Invariably, any options or actions 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 and concentrations of carbon dioxide in the atmosphere. That management involves both reducing sources of atmospheric carbon dioxide like the combustion of fossil fuels, or enhancing sinks such as uptake and storage or sequestration in vegetation and soils. In either case, formulation of options by decision makers and successful management of the earth's carbon budget requires solid scientific understanding of the carbon cycle.

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

North America is responsible for approximately 27% of the carbon dioxide emissions produced globally by fossil fuel combustion. The United States accounts for 86% of the North American total and approximately one quarter of the global total. In recent years, extraction of fossil fuels and their conversion into energy delivery forms (solid, liquid, gas, and electric) in North America released on the order of 2800 million metric tons (Mt) of CO_2 per year to the atmosphere, approximately 10% of total global emissions in 2003. Electricity generation is responsible for most (90-95%) of North America's energy extraction and conversion emissions. The transportation sector of North America released 2151 Mt CO_2 into the atmosphere in 2003, 40% of the total carbon emissions from worldwide transportation activity and about 9% of total global CO_2 emissions. The buildings sector in North America is responsible for the annual emission of 2712 Mt CO_2 or 9% of global fossil fuel emissions. U.S. buildings alone are responsible for more CO_2 emissions than total CO_2 emissions of any country in the world, except China. Most—approximately 64%—of the emissions from the building sector of North America are associated with the production of electricity used in buildings. Emissions from the North American building sector, excluding electricity, were about 4% of global total CO_2 emissions in 2003. In 2002, North American industry (excluding fossil fuel mining and processing) was responsible for the release of 826 Mt CO_2 into the atmosphere, or 16% of the 5200 Mt CO_2 emissions from global industry.

The carbon budget of North America is dominated by the fossil fuel emissions source; however, the vegetation and soils of North America and the surrounding coastal oceans are also a substantial net sink. Approximately 30% of North American fossil fuel emissions are offset by a smaller sink of 2170 Mt CO_2 per year. Most (60%) of that sink is caused by relatively young, growing forests in the United States and Canada which have re-colonized land formerly cleared of forests for agricultural use in past centuries. The *global* terrestrial sink is quite uncertain, estimated as somewhere in the range of 2200 to 8433 Mt CO_2 per year during the 1990s, with the actual sink likely near 4000 Mt CO_2 per year. Thus, North America is probably responsible for at least half of the global terrestrial sink, but could account for as little as a quarter to nearly all of it.

Both as a source and a sink, North America is a major, even dominant component of the global carbon cycle. And it is clear that the North American carbon budget of the next few decades will continue to be dominated by the large sources from fossil fuel emissions as the trends responsible for current emissions continue into at least the near future. Consequently, the global carbon cycle will continue to be dominated by a large fossil fuel source from North America. The future trajectory of carbon sinks in North America, and their contribution to the global terrestrial sink is less certain, in part because the important contribution 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 CO_2 concentrations is uncertain.

Because North America's carbon budget is such a substantial part of the global carbon budget, options and measures taken to manage the North American carbon budget will have important global consequences. North America has many opportunities for decreasing emissions, including changes to the energy system, increasing energy efficiency, investments in forest planting and agricultural soil management, biomass energy, and geological sequestration. Implementation of policies to deploy these technologies and practices is best achieved by national governments with international cooperation. This provides maximum coverage of CO_2 emissions and carbon sinks. It also allows better allocation of resources for technology research and development.

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

The Sources

The primary source of carbon in North America is the release of CO_2 during the combustion of fossil fuels. The North American fossil fuel source is three times larger than the net sink of land and water systems and dominates the net carbon balance of the continent. Fossil fuel carbon emissions in the United States, Canada and Mexico totaled 1856 Mt C (6805 Mt CO_2) in 2003 and have increased at an average rate of approximately 1% per year for the last 30 years. The United States was responsible for 85% of North America's fossil fuel emissions in 2003, Canada for 9% and Mexico 6%.

U.S. emissions dominate North American emissions and continue to grow at close to the North American average rate of ~1.0% per year, but U.S. per capita emissions have been roughly constant for the past 30 years, while the carbon intensity of the U.S. economy has decreased at a rate of ~2% per year. U.S. 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). Also, a large part of the decline in the carbon intensity of the U.S. economy was caused by the comparatively rapid growth of the service sector (3.6% per year), which now dominates the economy (roughly three-fourths of GDP) and has carbon emissions per dollar of economic activity only 15% that of manufacturing. This implies that emissions growth is essentially decoupled from economic growth. Also, 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.

Electricity generation is the single largest contributor to the North American fossil-fuel source, accounting for approximately 40% of the total North American fossil fuel source. Again, U.S. emissions dominate. In 2003, electricity generation in the United States alone released 2409 Mt CO_2 to the atmosphere, 35% of total North American fossil fuel emissions for that year.

The transportation sector of North America released 2120 Mt CO_2 into the atmosphere in 2003, 31% of total North American emissions. Most (87%) of that source is from the United States. Transportation energy use in North America and the associated CO_2 emissions have grown substantially and relatively steadily over the past forty years. Growth has been most rapid in Mexico, the country most dependent upon road transport. Carbon emissions from the transportation sector are determined by the levels of passenger and freight activity, the shares of transport modes, the energy intensity of passenger and freight movements, and the carbon intensity of transportation fuels. The growth of passenger and freight activity are driven by population, per capita income, and economic output. Chiefly as a result of economic growth, energy use by North American transportation is expected to increase by 46% from 2003 to 2025.

More than half of electricity produced in North America (67% in the United States) is consumed in buildings, making that single use the third largest carbon source in North America (25% of the total). The trend in the buildings sector over the last decade has been towards growth, with emissions from energy use in buildings in the United States and Canada (including the use of natural gas, wood, and other fuels as well as electricity) increasing 30% since 1990, corresponding to an annual growth rate of 2.1%. In the United States, the major drivers of energy consumption growth in the buildings sector are growth in commercial floor space and increase in the size of the average home. Carbon emissions from buildings will grow with energy consumption, which in turn will increase with population and income. Furthermore, the shift from large extended- to nuclear-family and single-occupant households means an increase in the number of households per unit population—each with its own heating and cooling systems and electrical appliances. Certain electrical appliances (such as space cooling/conditioning equipment) once considered a luxury are now becoming commonplace. Technology- and market-driven improvements in efficiency are expected to continue for most equipment, but this will probably not be sufficient to adequately curtail emissions growth in the buildings sector without government intervention.

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 fossil fuel source. Industrial CO_2 emissions from North America decreased nearly 11% between 1990 and 2002, while energy consumption in the United States and Canada increased 8% to 10% during that period. In both countries, a shift in production toward less energy-intensive industries and dissemination of more energy efficient equipment kept the rate of energy demand growth lower than industrial GDP growth.

The Sinks

Approximately 30% of North American fossil fuel emissions are offset by a natural sink of 592 Mt C per year caused by a variety of factors, including forest regrowth, fire suppression, and agricultural soil conservation. The sink currently absorbs 506 Mt C per year in the United States and 134 Mt C per year in Canada. Mexican ecosystems create a net source of 48 Mt C per year, mostly as a consequence of ongoing deforestation. The coastal ocean surrounding North America is also a small net source of carbon to the atmosphere (19 Mt C per year)

The primary carbon sink in North America is that of growing forests in the United States and Canada that have re-colonized land formerly cleared of forests for agricultural use in past centuries. Forest regrowth transfers carbon from the atmosphere, and it accumulates primarily in aboveground vegetation, with about a third accumulating as dead organic carbon in the soil. The suppression of forest fires also increases net carbon storage in forest biomass. The forest sink is by far the largest single component of the net North American sink, currently responsible for approximately 358 Mt C per year, or 60% of the total. As the recovering forests mature, however, net carbon uptake and the size of the sink decline; the estimated forest sink in Canada declined by nearly a third between 1990 and 2003.

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 level of approximately 80 million hectares burned per year, and this favors shrubs and trees in competition with grasses. The resulting sink has been estimated at 120 Mt C per year (20% of the North American sink), but the uncertainty around this estimate is greater than 100%. Woody encroachment might actually represent a small source of atmospheric carbon, or the sink might be twice the current estimate.

Wood products and wetlands are sinks of comparable size, 67 and 70 Mt C per year, respectively, or about 12% each of the total North American sink. Wood products create a carbon sink because they accumulate both in use (e.g., furniture, house frames, etc.) and in landfills. The wetland sink is primarily a consequence of peat accumulation in Canada's extensive frozen and unfrozen wetlands and of sedimentation and the accompanying carbon sequestration in mineral soils of Canadian and U.S. wetlands. Drainage of peatlands in the United States has created a net source of 5 Mt C per year, and the very large reservoir of carbon in North American wetlands (the single largest carbon pool of any North American ecosystem) is vulnerable to release to the atmosphere in response to climate change and drainage for development, shifting this moderate sink to a potentially large source.

Agricultural lands in North America are currently nearly neutral with respect to carbon. Although mineral soils are estimated to be sequestering currently 6–15 Mt C per year, cultivation of organic soils releases 5–10 Mt C per year. The net is an approximate carbon balance for agricultural soils in Canada and a small sink 6 Mt C year or even source (1.5 Mt C per year) in the United States. The carbon balance of agricultural lands is determined by two processes: management and changes in the environment. 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 sequestration in recent years. The effects of climate are uncertain.

Conversion of agricultural and wildlands to cities and other human settlements affect carbon sinks mainly by replacing biological ecosystems with built land cover. Growth of urban and suburban trees in North America are a part of the forest sink discussed above, but the rates of carbon sequestration in the vegetation and soils of settlements are uncertain and probably relatively small, certainly in comparison to fossil fuel emissions these areas. Thus, settlements in North America are almost certainly a source of atmospheric carbon, and the density and development patterns of human settlements are drivers of fossil fuel emissions, especially in the important residential and transportation sectors.

What are the direct, non-climatic effects of increasing atmospheric CO2 or other changes in the carbon cycle on the land and oceans of North America?

The consequences of a carbon cycle imbalance and the buildup of CO_2 in the atmosphere CO_2 extend beyond climate change alone. Ocean acidification and "CO_2 fertilization" of land plants are foremost among these direct, non-climatic effects.

The increasing concentration of CO_2 in the atmosphere has already made the world's oceans more acid. 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.

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. There is, however, considerable uncertainty 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 or net uptake and storage by terrestrial ecosystem. Recent studies include many examples in which experimental treatment with elevated CO_2 leads to consistent increases in plant growth, but others in which elevated CO_2 has little effect on plant growth, leads to an initial stimulation but limited long-term effects, or increases carbon losses as well as gains. 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 CO_2, it seems likely that extended deep drought or other unfavorable climatic conditions could mitigate the positive effects of elevated CO_2 on plant growth. It is thus far from clear that elevated concentrations of atmospheric CO_2 have led to terrestrial carbon sequestration or will do so at the continental scale in the future.

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 carbon cycle of the land and ocean of North America as part of purposeful carbon management will consequently affect these other processes and cycles. For example, an increase in organic carbon in soils is likely to increase both the availability of nitrogen for plant growth and enhance the water holding capacity of the soil. However, very little is known about the complex web of interactions between carbon and other systems at continental scales, and the direct, non-climatic effects of carbon cycle change or management on the interwoven systems of North America is essentially unknown.

What are the options and measures implemented in North American that could significantly affect the North American and global carbon cycles (e.g., North American sinks and global atmospheric CO_2 concentrations)?

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

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 biomass, and in the longer run (after 2025) hydrogen energy;
- Reducing the carbon emission impact of 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, and reduced demands due to increased end use efficiency.

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 cost-effective emission reduction vs. carbon sequestration at modest cost increases per metric ton of CO_2 emitted. Some economic analyses suggest that the potential mitigation is greater at relatively low prices for agricultural soil carbon sequestration than from fossil fuel use reduction. In addition, analyses suggest that carbon emission cap and trading policies could reduce carbon emissions significantly without a major net economic cost by providing incentives to use the least-cost combination of mitigation/sequestration alternatives.

Many options and measures that reduce emissions and increase sequestration have significant co-benefits in terms of economic efficiency and environmental management. At the same time, actions focused on one greenhouse gas or one mitigation pathway can have unintended consequences. For instance, carbon sequestration strategies such as reduced tillage can increase emissions of CH_4 or N_2O.

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 GHG emission reductions. For cities, one focus has been the Cities for Climate Protection program of International Governments for Local Sustainability (formerly ICLEI). For states, the Regional Greenhouse Gas (Cap and Trade) Initiative is nearing implementation. For industry, one focus has been membership in the Pew Center.

How can we improve the application of scientific information to decision support for carbon management and climate decision making?

Effective carbon management requires that relevant, appropriate science be communicated to the wide variety of people whose decisions affect carbon cycling. 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. Public concern, voluntary action and governmental efforts to regulate carbon emissions have heightened demand for basic data on the carbon cycle, models that link natural and social systems, and physical, economic and political analysis of specific carbon management options. There appears to 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 they 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, we suggest that leaders in the carbon science community take 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 both incremental and major departures from existing practice with the goal 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.

[This page intentionally left blank]