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[*For Internal Expert/Peer Review*]

The First State of the Carbon Cycle Report (*SOCCR*): The North American Carbon Budget and Implications for the Global Carbon Cycle

U.S. Climate Change Science Program

Synthesis and Assessment Product 2.2

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PREFACE

A primary objective of the U.S. Climate Change Science Program (CCSP) is to provide the best possible scientific information to support public discussion, as well as government and private sector decision-making, on key climate-related issues. To help meet this objective, the CCSP has identified an initial set of 21 synthesis and assessment products that address its highest priority research, observation, and decision-support needs.

This CCSP Report, which is one of the 21 products, provides a synthesis and integration of the current knowledge of the North American carbon budget and its context within the global carbon cycle. In a format useful to decision makers, it (1) summarizes our knowledge of carbon cycle properties and changes relevant to the contributions of and impacts[1] upon the United States and the rest of the world, and (2) provide scientific information for U.S. decision support focused on key issues for carbon management and policy. Consequently, this Report promises to be of significant value to decision-makers, and to the expert scientific and stakeholder communities. For example, we expect this Report to be a major contributor to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (due to be published in 2007).

This Report—Synthesis and Assessment Product (SAP) 2.2—addresses carbon emissions; natural reservoirs and sequestration; rates of transfer; the consequences of changes in carbon cycling on land and the ocean; effects of purposeful carbon management; effects of agriculture, forestry, and natural resource management on the carbon cycle; and the socio-economic drivers and consequences of changes in the carbon cycle. It covers North America's land, atmosphere, inland waters, and adjacent oceans, where "North America" is defined as Canada, the United States of America, and Mexico. The Report includes an analysis of North America's carbon budget that documents the state of knowledge and quantifies the best estimates (i.e., consensus, accepted, official) and uncertainties. This analysis provides a baseline against which future results from the North American Carbon Program (NACP) can be compared. SAP 2.2 will be coordinated with other CCSP synthesis and assessment products as appropriate, especially SAP 2.1 (*Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations and Review of Integrated Scenario Development and Application*) and SAP 3.1 (*Climate Models: An Assessment of Strengths and Limitations for User Applications*).

[1]The term "impacts" as used in this Report refers to specific effects of changes in the carbon cycle, such as acidification of the ocean, the effect of increased CO_2 on plant growth and survival, and changes in concentrations of carbon in the atmosphere. The term is not used as a shortened version of "climate impacts," as was adopted for the *Strategic Plan for the U.S.Climate Change Science Program*.

The focus of this Report follows the Prospectus developed by the Climate Change Science Program and posted on its website at www.climatescience.gov. More specifically, SAP 2.2 attempts to:

- Quantify current information on sources and sinks and associated uncertainties related to the buildup of carbon dioxide (CO_2) and methane (CH_4) in the atmosphere. For example, it provides the best available estimates of the contribution of carbon dioxide emissions from combustion of fossil fuels in North America to changes in global atmospheric concentrations of carbon dioxide for recent decades. Discussion of future changes in fossil fuel emissions are limited to existing scenarios because scenarios are the central element of the work being done under SAP 2.1.
- Discuss and assess current accepted projections of the future of the North American carbon budget, including uncertainties in projected fossil fuel emissions and the impact of policy and technology scenarios on those emissions.
- Provide current estimates, with the associated uncertainties, of the fractions of global and North American fossil-fuel carbon emissions being taken up by North America's ecosystems and adjacent oceans.
- Provide current, best available answers to specific questions about the North American carbon budget relevant to carbon management policy options. The key questions were identified through early and continuing dialogue with SAP 2.2 stakeholders. The answers include explicit characterization of uncertainties.
- Identify where NACP-supported research will reduce current uncertainties in the North American carbon budget and where future enhancements of NACP research can best be applied to further reduce critical uncertainties.
- Describe and characterize the carbon cycle as an integrated interactive system, using innovative graphics to depict the carbon cycle in ways that are easily understandable.

The audience for SAP 2.2 includes scientists, decisionmakers 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. This broad audience is indicative of the diversity 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. Not all the scientific information needs of this broad audience can be met in this first synthesis and assessment product, but the scientific information provided herein is designed to be understandable by all. The primary users of SAP 2.2 are likely to be

officials involved in formulating climate policy, individuals responsible for managing carbon in the environment, and scientists involved in assessing and/or advancing the frontier of knowledge.

It is envisioned that SAP 2.2 will be used (1) as a state-of-the-art assessment of our knowledge of carbon cycle properties and changes relevant to the contributions of and carbon-specific impacts upon the United States in the context of the rest of the world; (2) as a contribution to relevant national and international assessments; (3) to provide the scientific basis for decision support that will guide management and policy decisions that affect carbon fluxes, emissions, and sequestration; (4) as a means of informing policymakers and the public concerning the general state of our knowledge of the global carbon cycle with respect to the contributions of and impacts on the United States; and (5) as a statement of the carbon cycle science information needs of important stakeholder groups. For example, well-quantified regional and continental-scale carbon source and sink estimates, error terms, and associated uncertainties will be available for use in U.S. climate policy formulation and by resource managers interested in quantifying carbon emissions reductions or carbon uptake and storage. This Report is also intended for senior managers and members of the general public who desire to improve their overall understanding of the U.S. role in Earth's carbon budget and to gain perspective on what is and is not known.

The questions addressed by this Report include:

- What is the carbon cycle and why should we care?
- How do North American carbon sources and sinks relate to the global carbon cycle?
- What are the primary carbon sources and sinks in North America, and how are they changing and why?
- 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?
- What are the options and measures implemented in North America that could significantly affect the North American and global carbon cycles (e.g., North American sinks and global atmospheric concentrations of carbon dioxide)?
- How can we improve the application of scientific information to decision support for carbon management and climate decision making?

These questions provide the basis for the five chapters in Part I of this Synthesis and Assessment Report. Part II of the Report focuses on the human-system components of the North American carbon cycle, and discusses the carbon "sources and sinks" aspects of (a) energy extraction and conversion,

(b) the transportation sector, (c) industry and waste management, and (d) the buildings sector. Part III provides information about land and water systems, including human settlements, and their roles in the carbon cycle.

[NOTE TO REVIEWERS: The following items will also be included in the PREFACE, but have not yet been developed.]

- Structure and organization of this report; How to read this report
- Definition of basic terms, acronyms, units, etc.
- Treatment of carbon vs CO_2 vs CO_2 equivalents
- Treatment of CH_4
- Treatment of greenhouse gases
- Conventions for sources and sinks (i.e., positive and negative numbers)

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

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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.

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

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

Lead Authors: SOCCR Coordinating Team

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WHY A REPORT ON THE CARBON CYCLE?

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

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

All of the components of this cycle—the atmosphere, the terrestrial vegetation, soils, freshwater lakes and rivers, the ocean, and geological sediments—are reservoirs of carbon. As carbon cycles through the system, it is exchanged between reservoirs, transferred from one to the next. The carbon *budget* is an accounting of the balance of exchanges of carbon among the reservoirs: how much carbon is stored in a reservoir at a particular time, how much is coming in from other reservoirs, and how much is going out. When the inputs to a reservoir (the sources) exceed the outputs (the sinks), the amount of carbon in the reservoir increases. The myriad physical, chemical, and biological processes that transfer carbon among

reservoirs, and transform carbon among its various molecular forms during that transfer, are responsible for the cycling of carbon through reservoirs. That cycling determines the balance of the carbon budget observed at any particular time. Examining the carbon budget not only reveals whether the budget is in balance or imbalance, but also provides insight into causes of any imbalance and steps that might be taken to manage that imbalance. Currently, the global carbon budget is in imbalance; and human use of coal, petroleum, and natural gas to fuel economies is responsible.

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

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

The Carbon Cycle and Climate Change

Most of the carbon in the earth's atmosphere is in the form of carbon dioxide (CO_2) and methane (CH_4). Both carbon dioxide and methane are important "greenhouse gases." Along with water vapor, and other "radiatively active" gases in the atmosphere, they absorb heat radiated from the earth's surface, heat that would otherwise be lost into space. As a result, these gases help warm the earth's atmosphere. Rising concentrations of atmospheric carbon dioxide and other greenhouse gases can alter the earth's radiant energy balance. The earth's energy budget determines the global circulation of heat and water through the atmosphere and the patterns of temperature and precipitation we experience as weather and climate. Thus, the human disturbance of the earth's global carbon cycle during the Industrial era and the resulting imbalance in the earth's carbon budget and buildup of carbon dioxide in the atmosphere have consequences for climate and climate change. According to the Strategic Plan of the U.S. Climate Change Science Program, carbon dioxide is the largest single forcing agent of climate change (CCSP, 2003).

In addition to the relationship between climate change and atmospheric carbon dioxide as a greenhouse gas, research is beginning to reveal the feedbacks between a changing carbon cycle and changing climate and what that implies for future climate change. Simulations with climate models that include an interactive global carbon cycle indicate a positive feedback between climate change and atmospheric carbon dioxide concentrations. The research is in its early stages, and the magnitude of the feedback varies considerably among models; but in all cases, future atmospheric carbon dioxide concentrations are higher and temperature increases are larger in the coupled climate-carbon cycle simulations than in simulations without the coupling and feedback between climate change and changes in the carbon cycle (Friedlingstein *et al*., 2006).

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

Other Implications of an Imbalance in the Carbon Budget

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

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

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

Why the Carbon Budget of North America?

The continent of North America has been identified as both a significant source and a significant sink of atmospheric carbon dioxide (Wofsy and Harriss, 2002). More than a quarter (27%) of global carbon emissions from the combination of fossil fuel and cement manufacturing are attributable to North America (United States, Canada, and Mexico) (Marland *et al*., 2003). North American plants remove carbon dioxide from the atmosphere and store it as carbon in plant biomass and soil organic matter, mitigating to some degree the anthropogenic sources. The magnitude of the "North American sink" has been estimated at anywhere from less than 100 Mt C yr^{-1} to slightly more than 2000 Mt C y^{-1} (Turner *et al*., 1995; Fan *et al*., 1998), with a value near 350 to 750 Mt C yr^{-1} perhaps most likely (Houghton *et al*., 1999; Goodale *et al*., 2002; Gurney *et al*., 2002). The North American sink is thus a substantial fraction, perhaps on the order of 30–60%, of the global terrestrial sink estimated to be in the range of 600 to 2300 Mt C yr^{-1} and primarily in the extra-tropical Northern Hemisphere (IPCC, 2001). The global terrestrial sink is responsible for about a quarter to a half of the carbon added to the atmosphere by human actions that was transferred to oceans and land by carbon cycle processes and thus did not contribute to the accumulation and increase of carbon dioxide in the atmosphere. Global atmospheric carbon concentrations would be substantially higher than they are without the partially mitigating influence of the sink in North America.

Some mechanisms that might be responsible for the North American terrestrial sink are reasonably well known. These mechanisms include, but are not limited to, the re-growth of forests following abandonment of agriculture, changes in fire and other disturbance regimes, historical climate change, and fertilization of ecosystem production by nitrogen deposition and elevated atmospheric carbon dioxide (Dilling *et al*., 2003). Recent studies have indicated that some of these processes are likely more important than others for the current North American carbon sink, but significant uncertainties remain (Caspersen *et al.*, 2000; Schimel *et al*., 2000; Houghton 2002). The future of the current North American terrestrial sink is highly uncertain, and it depends on which mechanisms are the dominant drivers.

Estimates of coastal carbon cycling and input of carbon from the land are equally uncertain (JGOFS, 2001). Coastal processes are also difficult to parameterize in global carbon cycle models, which are often used to derive best-guess estimates for regional carbon budgets (JGOFS, 2001). It is very important to

quantify carbon fluxes in coastal margins of the area adjacent to the North American continent, lest regional budgets of carbon on land be mis-attributed.

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

CARBON CYCLE SCIENCE IN SUPPORT OF CARBON MANAGMENT DECISIONS

Beyond understanding the science of the North American carbon budget and its drivers, increasing attention is now being given to deliberate management strategies for carbon (DOE 1997, Hoffert *et al.*, 2002; Dilling *et al.*, 2003). Carbon management is now being considered at a variety of scales in North America. There are tremendous opportunities for carbon cycle science to improve decision-making in this arena. In seeking ways to more effectively use scientific information in decision-making, we must pay particular attention to the importance of developing constructive scientist–stakeholder interactions.

Many decisions in government, business, and everyday life are connected with the carbon cycle. They can relate to *driving forces* behind changes in the carbon cycle (such as consumption of fossil fuels) and strategies for managing them and/or *impacts* of changes in the carbon cycle (such as climate change or ocean acidification) and responses to reduce their severity. Carbon cycle science can help to inform these decisions by providing timely and reliable information about facts, processes, relationships, and levels of confidence, although such support is more likely to be effective if the science is connected with communication structures that are considered by both scientists and users to be legitimate and credible.

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

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

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

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

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

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

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

The U.S. climate and carbon research community, and a diverse range of stakeholders, recognize the need for an integrated synthesis and assessment focused on North America to (a) summarize what is known and what is known to be unknown, documenting the maturity as well as the uncertainty of this knowledge; (b) convey this information among scientists and to the larger community; and (c) ensure that our studies are addressing the questions of concern to society and decision-making communities.

As the most comprehensive treatment to date of carbon cycle facts, directions, and issues for North America, incorporating stakeholder interactions throughout, this report, the *First State of the Carbon Cycle Report (SOCCR)*, focused on *The North American Carbon Budget and Implications for the Global Carbon Cycle* is intended as a step in that direction.

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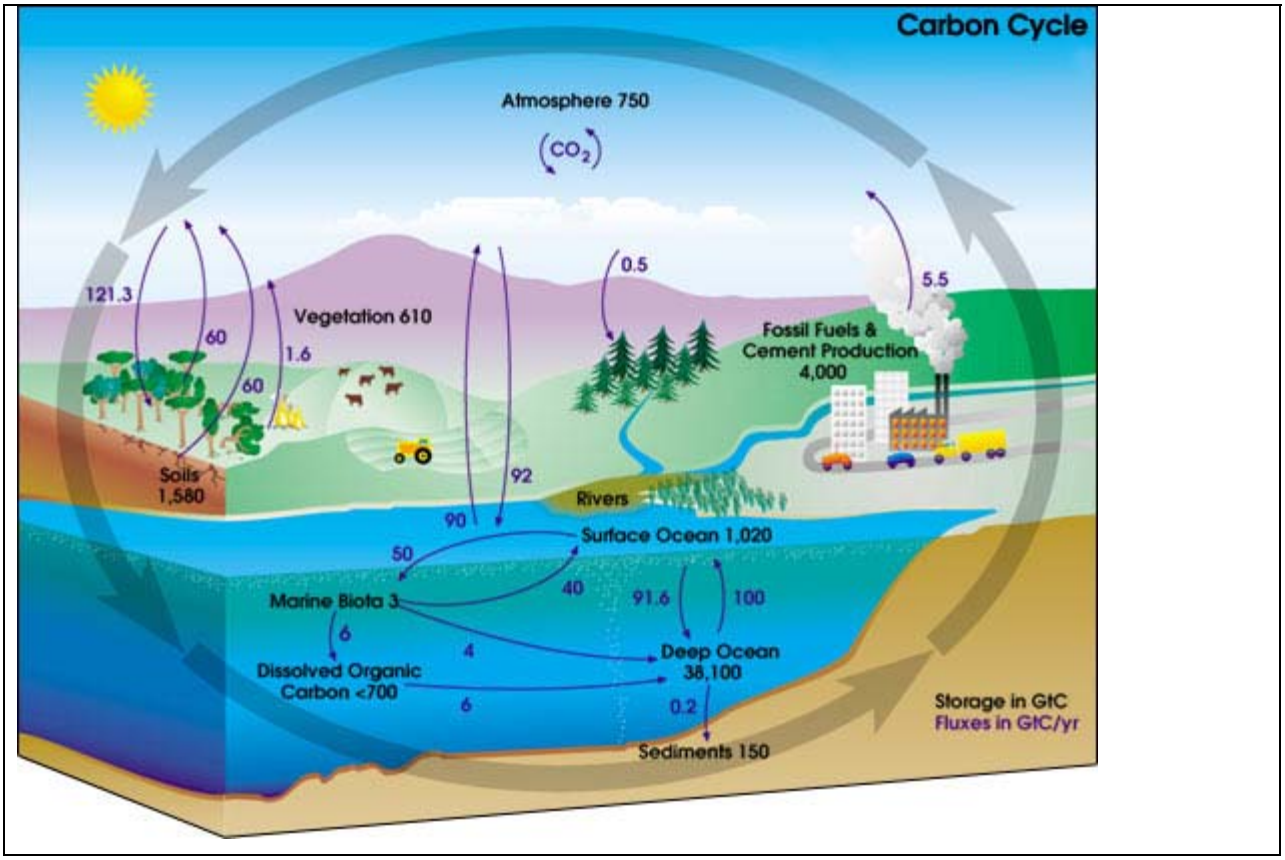

Figure 1-1. The global carbon cycle. Reservoirs (in black) are gigatons [1 Gt = one billion (1×10^9) metric tons] of carbon, and exchanges between reservoirs (in purple) are Gt carbon per year. *Illustration courtesy NASA Earth Science Enterprise*.

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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.
- While emissions (a carbon source) dominate the carbon budget of North America, these emissions are partially offset by 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. This sink is most likely caused by relatively young, growing forests which have re-colonized land formerly cleared of forests for agricultural use in past centuries.
- Global carbon dioxide emissions have increased for the last 30 years. In comparison, North American carbon dioxide emissions have increased at an average rate of approximately 1% per year for the last 30 years.
- 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. 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.

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 48% ± 5% of the carbon dioxide emitted to the atmosphere from fossil-fuel combustion and forest clearing has remained there (Sabine *et al*., 2004b). In essence, human actions have received a large subsidy from the unmanaged parts of the carbon cycle. This subsidy has sequestered, or hidden from the atmosphere, approximately 240 ± 40 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 carbon cycle.

Figure 2-2. Atmospheric CO_2 concentration from 1850 to 2005. The data prior to 1957 are from the Siple ice core (Friedli *et al*., 1986). The data since 1957 are from continuous atmospheric sampling at the Mauna Loa Observatory (Hawaii) (Keeling *et al*., 1976; Thoning *et al.*, 1989).

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 (Orr *et al*., 2005).

The Background or 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 or unmanaged 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 100–200 Gt of atmospheric carbon, approximately 20 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, with the difference burned in wildfires or stored as plant biomass or soil organic carbon. The second comprises the ocean carbon cycle: about 92 ± 5 Gt of atmospheric carbon dissolves annually in the oceans, and about 90 Gt moves from the oceans to the atmosphere. The rest remains in the ocean as a mix of dissolved CO_2, bicarbonate (HCO_3^-), carbonate ($CO_3^=$), and organic matter.

Before the beginning of the industrial revolution, carbon uptake and release through these two pairs of large fluxes were almost balanced, with carbon uptake on land of approximately 0.45 ± 0.1 Gt C yr^{-1} transferred to the oceans 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 (Keeling and Stephens, 2001; Sigman and Boyle, 2000). 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 plant growth, especially in the period 354 to 290 million years ago, the Carboniferous. During this period, 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. It also led to a near doubling of atmospheric oxygen (Falkowski *et al*., 2005).

Anthropogenic Perturbations

Since the beginning of the industrial revolution, or about 1850, 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 1850 through 2004 are just over 300 ± 30 Gt (Marland and Rotty, 1984; Andres *et al*., 1999). Land use change during this period, mostly from the clearing of forests, added another 160 ± 160 Gt (DeFries *et al*., 1999; Houghton, 1999). 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 1850, with atmospheric CO_2 rising by 31% (i.e., from 287 ppm to 377 ppm).

Together, the three major countries of North America (Canada, Mexico, and the United States) accounted, in 2003, for carbon emissions from fossil-fuel combustion of approximately 1.83 ± 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. The carbon intensity of the United States' economy, at 0.15 metric ton of emitted carbon per $1000 (in 1995 dollars) of GDP (measured as PPP or Purchasing Power Parity), in 2003 was close to the world's average of 0.14 tC/$1000 [DOE EIA (U.S. Department of Energy, 2005)]. Canada's carbon intensity is somewhat higher at 0.19 tC/$1000, and Mexico's is somewhat lower at 0.12 tC/$1000. Rich countries with substantially lower carbon intensity include Japan, France, the United Kingdom, and Germany. Rich countries with higher carbon intensity include Australia and New Zealand [DOE EIA (U.S. Department of Energy, 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. Carbon intensity in both China and India is high. In 2003, carbon intensity in China was 4.6 times greater than that in the United States. The carbon intensity in India was 3.4 times that in the United States [DOE EIA (U.S. Department of Energy, 2005)].

Carbon emissions from North America have grown by about 1.0% per year for the last 30 years, substantially slower than the growth in GDP (Fig. 2-3). Slower growth in emissions than GDP

characterizes many of the world's richest countries, including Canada and the United States. Since 1980, emissions growth has been only slightly slower than GDP growth in Mexico, a pattern typical of rapidly industrializing countries (Fig. 2-3). More rapid growth in GDP than in emissions can result from decreasing both the energy intensity of the economy (through, for example, more efficient manufacturing and increasing the role of the service sector) and the carbon intensity of the energy system (through, for example, replacing coal with natural gas in power plants or replacing fossil power plants with wind power plants) (Sathaye, 2004). It is not clear whether, in the absence of policy, historical trends in the energy intensity of GDP and the carbon intensity of the energy system will continue.

Figure 2-3. GDP in 2000 U.S. dollars vs fossil-fuel carbon emissions (Mt C yr^{-1}). Data from EIA (2005). Each arrow shows the sequence from 1980 to 2003 for a country. Note that carbon emissions per unit GDP decelerate as a country gains wealth. The lines in the figure show the slopes associated with the different ratios of GDP and emissions growth (the y-intercept of the dotted and dashed lines are not informative and were chosen only to keep from obscuring the arrows).

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 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. To date, estimates of continental-scale fluxes based on eddy flux must be regarded as preliminary.

Inventories, based on measuring trees on land (Birdsey and Heath, 1995) or carbon in 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 midlatitudes 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 passive tracers (Matsumoto *et al*., 2004) (^{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). 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, 1999). At present, model estimates are uncertain enough that they are often used most effectively in concert with other kinds of estimates (e.g., Peylin *et al*., 2005).

Inverse estimates based on atmospheric gases (CO_2, ^{13}C in CO_2, or O_2) infer surface fluxes based on the spatial 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 (Masarie and Tans, 1995). The ^{13}C in CO_2 and 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 (Siegenthaler and Oeschger, 1987). 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 460 ± 100 Gt carbon added to the atmosphere by human actions since 1850, only about 180 ± 5 Gt remain. The “missing carbon” was 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 is now in the oceans (Sabine *et al*., 2004a). This leaves about 100 Gt that must be stored on land. 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 (Gloor *et al*., 2003; Matear and McNeil, 2003; Matsumoto *et al*., 2004; Takahashi *et al*., 2002; Gurney *et al*., 2003). 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 (Fig. 2-4). 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).

Figure 2-4. The spatial distribution of ocean CO_2 exchange from 1992–1996 for several regions and measurement approaches. Tak99 and Tak02 are from (Takahashi *et al*., 2002) ΔpCO_2 estimates, T3L1 and T3L2 are from (Gurney *et al*., 2003; Gurney *et al*., 2004), Fwd is from predictive ocean models, JI is from the ocean atmosphere ocean inversions of (Jacobson *et al*., 2006). The far right column is the sum of the individual ocean basins toward the left [from (Jacobson *et al*., 2006)].

On land 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. 2-5). Fire likely plays a large role in this variability (van der Werf *et al*., 2004).

Figure 2-5. 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 approximately 80% of the carbon released to the atmosphere by human activities (Joos and Prentice, 2004). 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 (Goodale *et al*., 2002; Chen *et al*., 2003; Kurz and Apps, 1999)]. 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}. 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).

Recent carbon storage in North America probably results from a number of different processes. Chen *et al*. (Chen *et al*., 2003) argue that Canadian forests are a small sink because processes tending to increase tree growth, including elevated atmospheric CO_2 and deposition of biologically available nitrogen, are more than compensating effects of recent disturbances. Kurz and Apps (Kurz and Apps, 1999) reach the opposite conclusion, that recent disturbances make Canadian forests a net carbon source. In the United States, forest regrowth is outpacing recent harvesting and disturbance (Birdsey and Heath,

1995). Some of this is a consequence of a profound historical shift in the location of United States agriculture.

Much of the Eastern United States was cleared for agriculture in the 18th century, only to be abandoned as agriculture moved to the Great Plains, the Southwest, and the West in the 19th and 20th centuries (Ramankutty and Foley, 1999). As a consequence, large areas once cleared for agriculture are currently regrowing forests (Caspersen *et al*., 2000). Increasing carbon in previously harvested forests has several drivers beyond the shift in agriculture, including changes in harvesting and management practices (Harmon *et al*., 1996; Goodale *et al*., 2002) and fire suppression (Calkin *et al*., 2005; Mouillot and Field, 2005). The processes sequestering carbon have been partially offset by processes that release stored carbon, including unusually high wildfire years [United States—(Mouillot and Field, 2005)], insect outbreaks [Canada—(Kurz and Apps, 1999)] , and storm damage [Europe—(Janssens *et al*., 2003)]. The heat wave and drought in Europe in the summer of 2003 led to a large loss of carbon, driven largely by decreased plant growth (Ciais *et al*., 2005).

Several other processes probably contribute to recent carbon sinks in the United States (Table 2-1), though they are difficult to quantify with confidence. These include the thickening of vegetation in woodland and shrubland areas, the burial of organic matter in lakes and reservoirs (Stallard, 1998), increases in the soil carbon in managed grassland and agricultural soils (Asner *et al*., 2003), and storage of carbon in durable products (e.g. houses and furniture) and waste in landfills (Pacala *et al*., 2001).

Table 2-1. Sinks of carbon for 1980--90 in the coterminous United States (Gt C yr^{-1}).

Some of the recent carbon storage in North America may be a consequence of increased atmospheric CO_2 (Schimel *et al*., 2000; Melillo *et al*., 2003), nitrogen deposition (Holland *et al*., 1997), or climate changes that have increased the length of the frost-free season in many locations (Myneni *et al*., 1997; Hicke *et al*., 2002). The evidence in support of the first two mechanisms comes from empirical and modeling studies. It is clear that plant growth in many terrestrial ecosystems is limited by either atmospheric CO_2 or biologically available nitrogen (Melillo *et al*., 2003). It is much less clear, however, that increased availability of either resource has led to carbon sequestration. Recent studies include many examples in which experimental treatment with elevated CO_2 leads to consistent increases in plant growth (e.g., Norby *et al*., 2005), but others in which elevated CO_2 has little effect on plant growth (Shaw *et al*., 2002), leads to an initial stimulation but limited long-term effects (Oren *et al*., 2001), or increases carbon losses as well as gains (Hungate, 1997; Schlesinger and Lichter, 2001). Evidence on the role of changes in the length of the growing season comes from field-based, satellite, and modeling studies (Myneni *et al*.,

1997; Nemani *et al*., 2003). Recent evidence indicates that negative effects of dry summers can offset much or all of the effects of earlier springs (Angert *et al*., 2005).

To the extent that current carbon sink in North America reflects the regrowth of previously harvested forest, it is a one-time phenomenon and not a permanent feature of the carbon cycle. Similarly, a sink from effective fire suppression in the second half of the 20th century may have already saturated or even reversed, as large accumulations of highly flammable fuels amplify the challenge of current and future fire management. Sinks from CO_2 fertilization (Hungate *et al*., 2003), increased nitrogen deposition, and altered management of agricultural lands (Smith, 2004) could continue for some time, but they too will eventually saturate (Gruber *et al*., 2004).

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. Currently, as much as 50% of this may be offset by carbon uptake in plants and soils (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 (Hoffert *et al*., 2002; Caldeira *et al*., 2004; Pacala and Socolow, 2004). Many of these are in the area of increasing the efficiency of energy generation, the transportation system, building stocks, and manufacturing technologies. Others are in the area of replacing carbon-emitting energy technologies with nonemitting technologies, including solar, wind, biomass, and nuclear. Still others are in the area of sequestration, including both geological and biological components. Finally, there are many opportunities in conservation, in directing the economy and personal preferences away from carbon-intensive activities. Capitalizing on the opportunities in all four of these areas will require dedicated research, financial support, creativity, and an interested public (Raupach *et al*., 2004). Nothing about the status of the unmanaged carbon cycle provides a justification for decreasing the commitment to progress in all of these areas.

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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 carbon cycle.

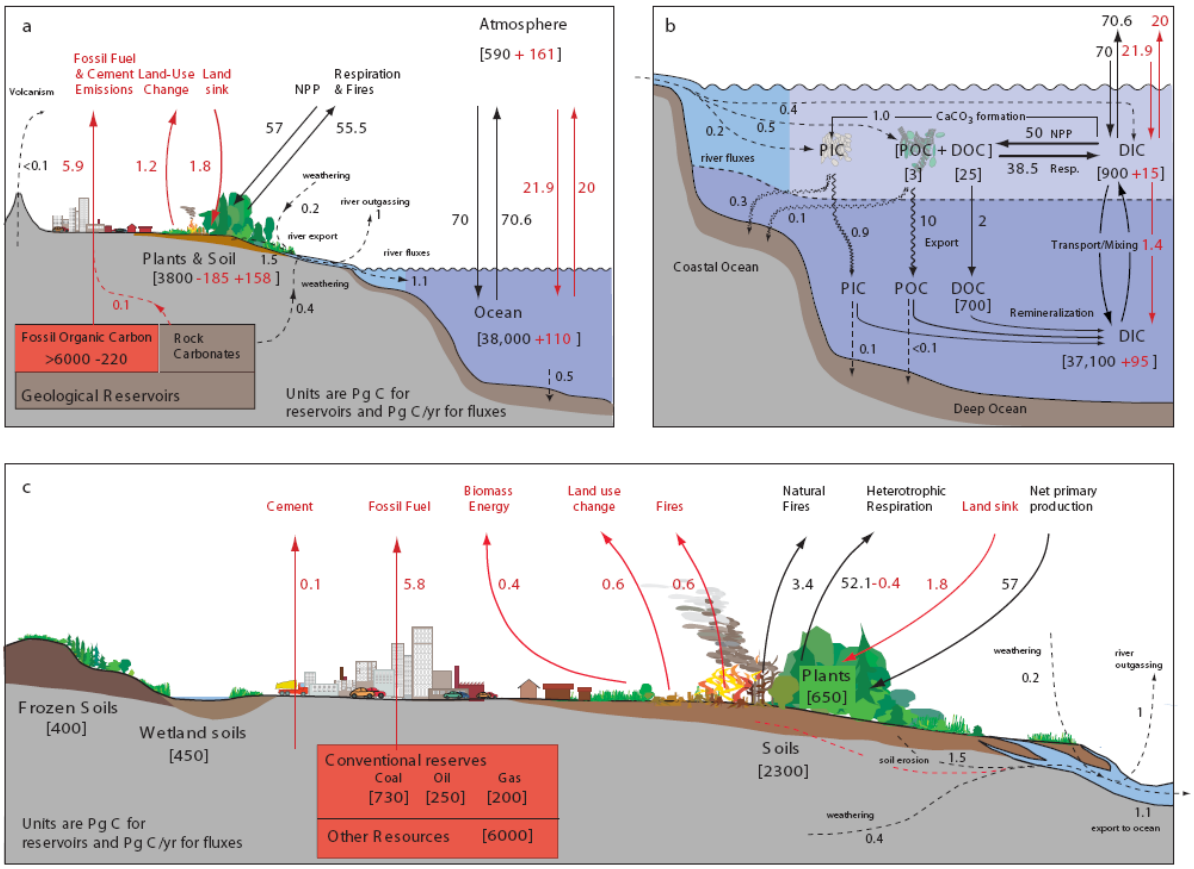
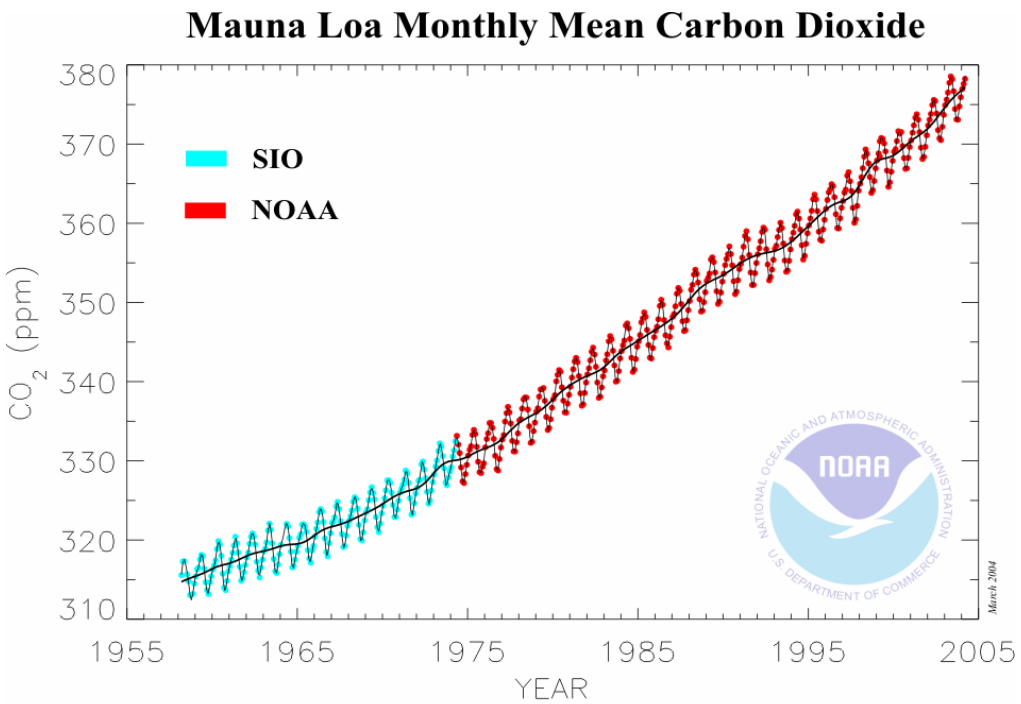


Fig. 2-2. Atmospheric CO_2 concentration from 1850 to 2005. The data prior to 1957 are from the Siple ice core (Friedli *et al*., 1986). The data since 1957 are from continuous atmospheric sampling at the Mauna Loa Observatory (Hawaii) (Keeling *et al*., 1976; Thoning *et al*., 1989).



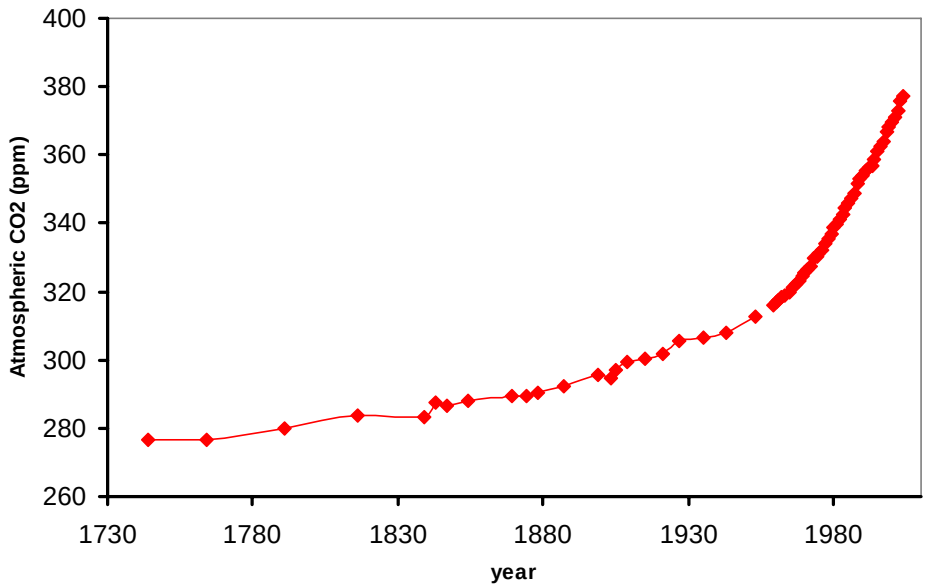


Figure 2-3. GDP in 2000 U.S. dollars vs fossil-fuel carbon emissions (Mt C yr^{-1}). Data from EIA (2005). Each arrow shows the sequence from 1980 to 2003 for a country. Note that carbon emissions per unit GDP decelerate as a country gains wealth. The lines in the figure show the slopes associated with the different ratios of GDP and emissions growth (the y-intercepts of the dotted and dashed lines are not informative and were chosen only to keep from obscuring the arrows).

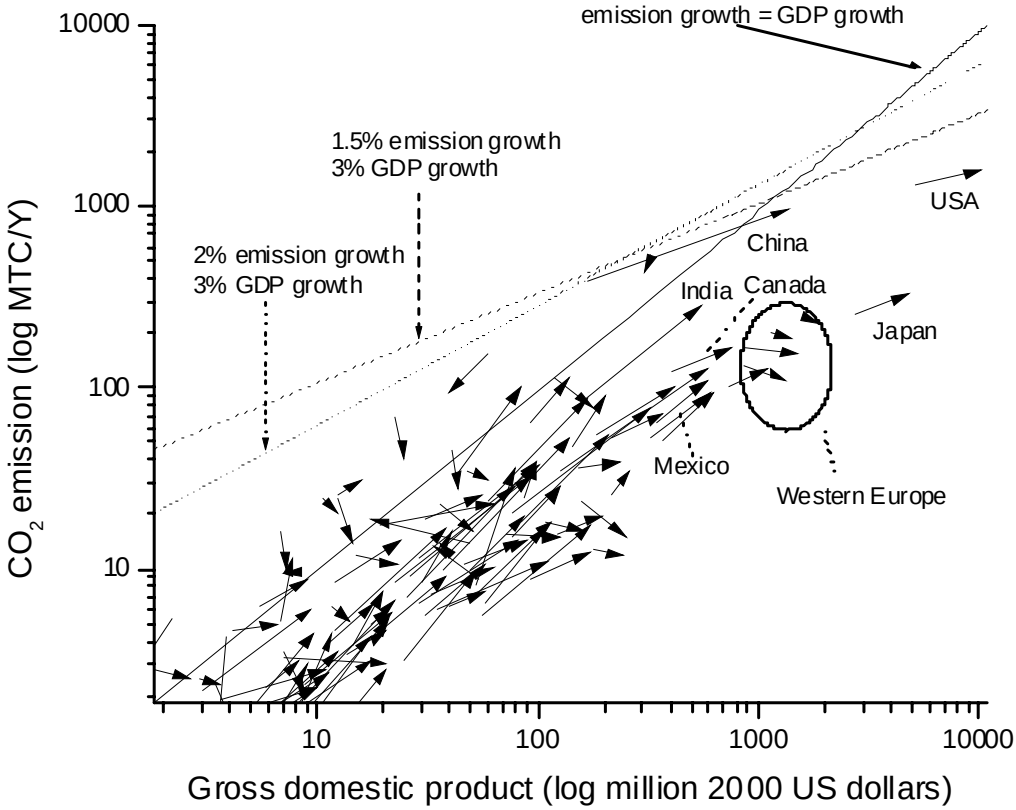


Figure 2-4. The spatial distribution of ocean CO_2 exchange from 1992–1996, for several regions and measurement approaches. Tak99 and Tak02 are from (Takahashi *et al.*, 2002) ΔpCO_2 estimates, T3L1 and T3L2 are from (Gurney *et al.*, 2003; Gurney *et al.*, 2004), Fwd is from predictive ocean models, JI is from the ocean atmosphere ocean inversions of (Jacobson *et al.*, 2006). The far right column is the sum of the individual ocean basins toward the left [from (Jacobson *et al.*, 2006)].

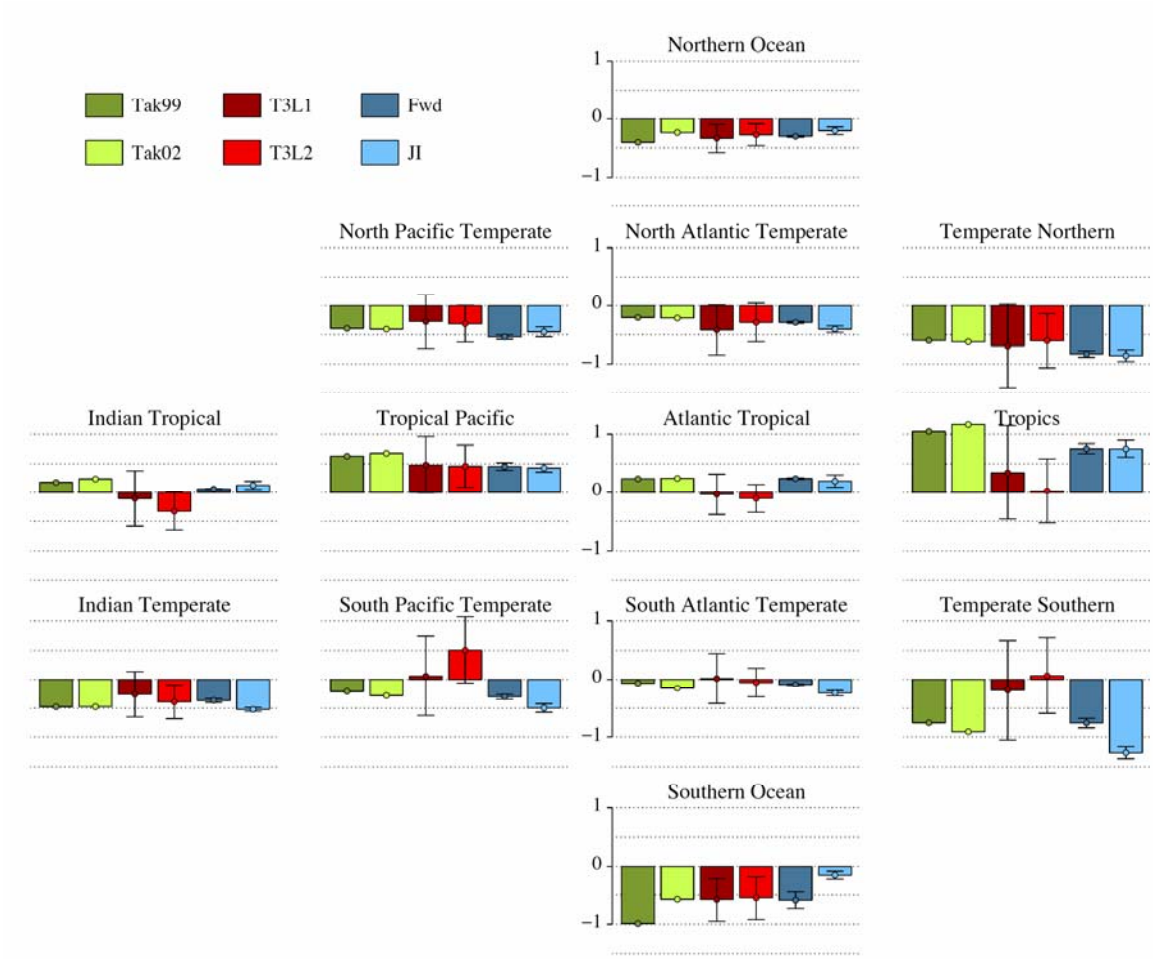
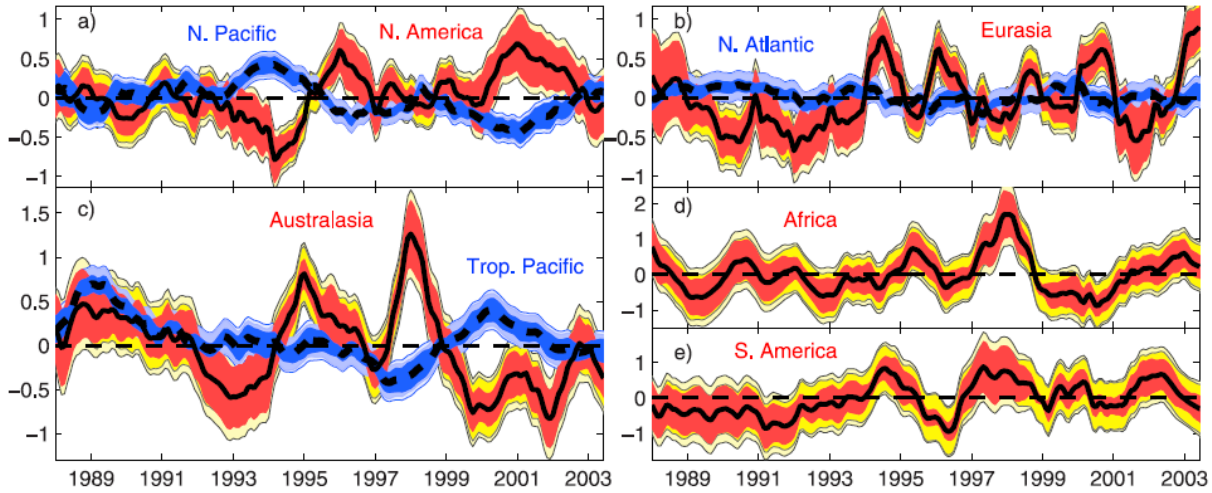


Figure 2-5. The 13-model mean CO_2 flux interannual variability (Gt C yr^{-1}) for several continents (solid lines) and ocean basins (dashed lines) (a) North Pacific and North America, (b) Atlantic north of 15ºN and Eurasia, (c) Australasia and Tropical Pacific, (d) Africa, and (e) South America (note the different scales for Africa and South America) [from (Baker *et al*., 2006)].



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 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 carbon. 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.

INTRODUCTORY SUMMARY

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 16.5% of the global land area, 7.4% of the global population, and 25.0% of global GDP (EIA, 2005).

Figure 3-1. Historical carbon emissions from fossil fuel in the United States, Canada, and Mexico. Data from EIA (2005).

The United States is the world's largest emitter in absolute terms, with approximately one-quarter of the global total. 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 ton 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 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 (see Figs. 3-1 to 3-3).

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). 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 (Figs. 3-3b to 3-3c). 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. This is important because it speaks to the issue of our technological readiness to achieve an emissions target. For example, a portfolio of technologies able to reduce the 1% annual growth in emissions to 0%, might be insufficient if carbon emissions were to begin rising at the ~3% growth rate of GDP (Pacala and Socolow, 2004).

Carbon Sinks (see Table 3-1 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 (i.e., 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 are small net emitters to the atmosphere at the continental scale (19 Mt C yr^{-1}) (see Chapter 15). However, much of the CO_2 absorbed from or emitted to the air by coastal waters is part of the natural carbon cycle of the oceans, and so coastal sea-air exchanges should also be excluded from the continental carbon sink.

As reported in Chapter 2, all of the world's continents collectively absorbed a net of approximately 1500 Mt C yr^{-1} of atmospheric CO_2 during the 1990s. However, because this value includes the losses of 1000–2000 Mt C yr^{-1} caused by tropical deforestation (Archard *et al*., 2002; DeFries *et al*., 2002; Houghton, 2003b), carbon sinks during the 1990s actually totaled 2500–3500 Mt C yr^{-1}. North America's

net absorption of more than 700 Mt C yr^{-1} thus represents 20–30% of the global total on 16.5% of the global land area. Similarly, the United States was responsible for 17–24% of the global total despite having only 6.5% of the land area (Table 3-1). 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.

The magnitude of the North American sink documented in Table 3-1 offers the possibility that significant carbon mitigation 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 value reported in Table 3-1. 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 four significant components of the carbon budget in Canada and six in Mexico (see Table 3-1).

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 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.

NORTH AMERICAN FOSSIL FUEL EMISSIONS

Fossil fuel emissions currently dominate the net carbon balance in the United States, Canada, and Mexico (Fig. 3-1, Table 3-1). Fossil emissions are more than three times larger than the net carbon sink in the United States, marginally larger than the net sink in Canada, and twice as large as the net deforestation source in Mexico. 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).

Carbon dioxide emissions continue to grow in North America at close to their 30-year average of 1.0% per year. Figure 3-2 shows the growth of GDP and CO_2 emissions in more than 100 countries from 1980 (tail of each arrow) until 2003 (arrow head). The vertical distance between the solid diagonal line and the average position of an arrow is inversely related to the country's relative carbon intensity. Note that the United States is no outlier in this respect. Also, the slope of an arrow shows the rate of emissions growth relative to the rate of economic growth—the flatter the slope, the faster the country's carbon intensity is decreasing. Thus, countries vertically close to the line have higher carbon intensities than countries far from the line. Note that the United States has a flatter slope than many countries including Japan, but that several other industrialized counties actually have growing GDP and declining emissions (the circled arrows).

Figure 3-2. GDP in 2000 U.S. dollars vs fossil fuel carbon emissions (Mt C yr^{-1}). Data from EIA (2005). Each arrow shows the sequence from 1980 to 2003 for a country. Note that carbon emissions per unit GDP decelerate as a country gains wealth. The lines in the figure show the slopes associated with the different ratios of GDP and emissions growth (the y-intercepts of the dotted and dashed lines are not important; we moved the lines representing different ratios of GDP and emissions growth to higher y-intercepts so as not to obscure the data summarized by the arrows).

Historical decreases in U.S. carbon intensity began early in the 20th century and continue despite the approximate stabilization of per capita emissions (Fig. 3-3a). 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. 3-3b). Because the service sector has a much lower carbon intensity than manufacturing (a factor of 6.5 in 2002; compare Figs. 3-3b and 3-3c), 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. 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. 3-3b and 3-3c). 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. 3-3c; 30-year average of 1.0% per year), while emissions from transportation are growing faster than the population but slower than GDP (Fig. 3-3c; 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 3-3. (a) 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 (red 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). (b) Historical U.S. GDP divided among the manufacturing, services and agricultural sectors. *Source*: Mitchell (1998) and WRI (2005). (c) Historical U.S. carbon emissions divided among the residential, services, manufacturing, and transportation sectors. *Source*: EIA (2005).

NORTH AMERICAN CARBON SINK

Appendix 3A contains an overview of the historical development of the sinks in U.S. and Canadian ecosystems and the source from ongoing deforestation in Mexico. The remainder of this chapter focuses on current values. To estimate non-fossil sources and sinks, we rely exclusively on 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. 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).

The current emissions of carbon by the United States, Canada, Mexico, and North America are listed in Table 3-1, and the much larger current stocks of ecosystem carbon are listed in Table 3-2 (note the change of units from millions of tons of carbon per year in Table 3-1 to billions of tons of carbon in Table 3-2). **In Table 3-1, a negative number indicates a carbon sink, and a positive number indicates a carbon source.**

Table 3-2. Carbon stocks in North America in billions of tons.

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) plus 23 Mt C yr^{-1} from urban and suburban trees (Chapter 14). 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} 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 now 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. 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). 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.

The two studies of 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.

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 1.5 to –6 Mt C yr^{-1} in the United States.

Wetlands

Peatlands are wetlands that have accumulated deep soil carbon deposits over thousands of years because decomposition in them is less than plant productivity. Thus, wetlands form the largest carbon pool of any North American ecosystem (Table 3-2). 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 report is on carbon fluxes without a consideration of the radiative forcing of different greenhouse gases [i.e., global warming potential (GWP)]. However, wetlands are naturally an important source of methane (CH_4). The GWP of a gas depends on its instantaneous radiative forcing and its lifetime in the atmosphere, with methane having GWPs of 1.9 and 16.9 CO_2-C equivalents on 500-year and 20-year time frames, respectively (Ramaswamy et al., 2001). 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 9). 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 reservoirs, alluvium, and colluvium 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 preindustrial 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

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.

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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]	–283
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 sink ***	–506	–134	48	–592
Net horizontal exports (negative) or imports (positive)				
Wood products****	14[e]	–74[c]	–1[d]	–61
Agriculture products***	–65[k]	ND	ND	–65
Rivers to ocean**	–35[k]	ND	ND	–35
Total net absorption** (Sink plus exports)	–592	–208	47	–753
Net absorption (negative) or emission (positive) by coastal waters ****	ND	ND	ND	19[l]

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
[i]Chapter 13
[j]Stallard, 1998; Pacala *et al*. (2001)
[k]Pacala *et al*. (2001)
[l]Chapter 15

Table 3-2. 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

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

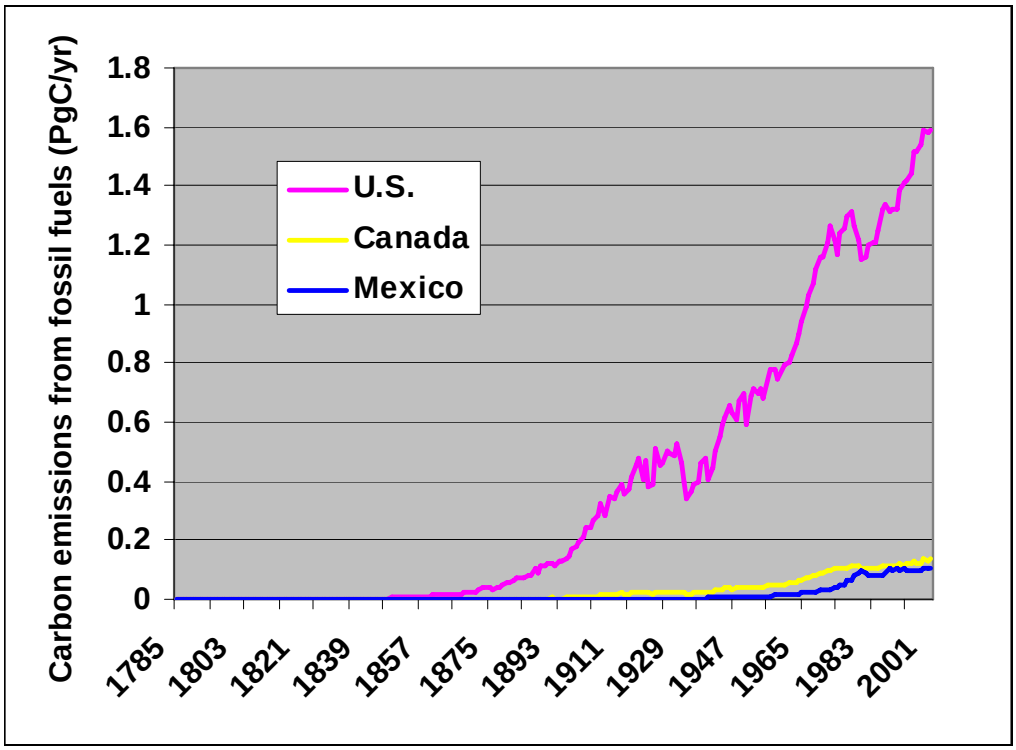


Fig. 3-1. Historical carbon emissions from fossil fuel in the United States, Canada, and Mexico. Data from EIA (2005).

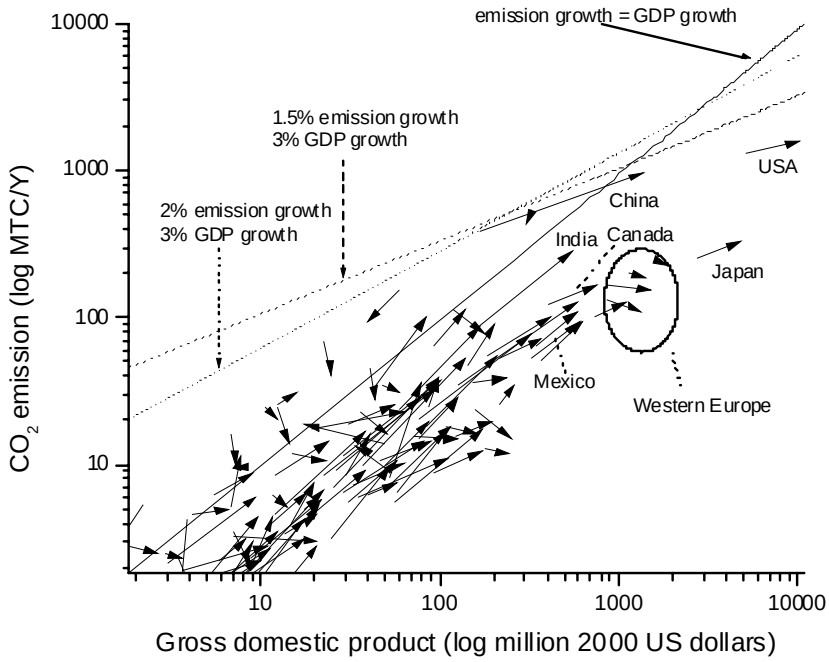
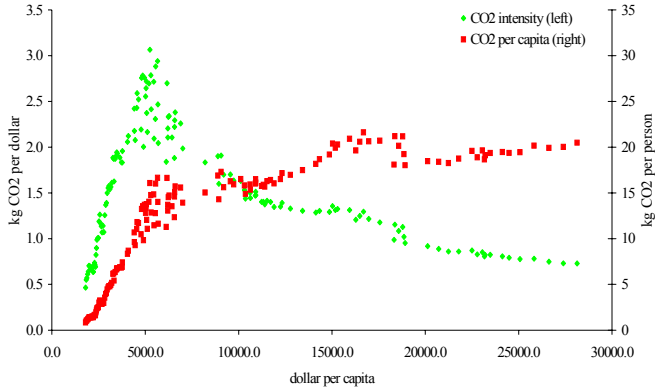
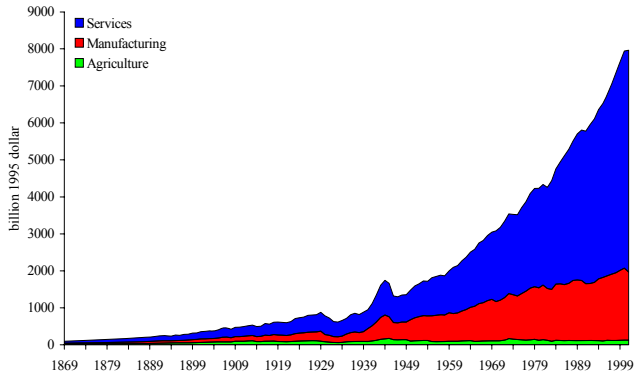


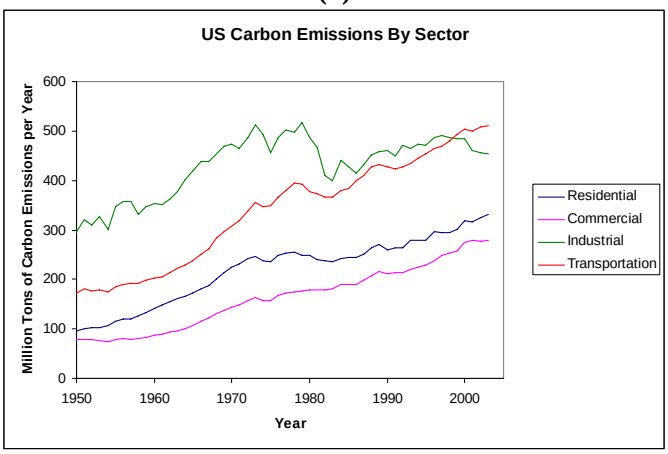
Fig. 3-2. GDP in 2000 U.S. dollars vs fossil fuel carbon emissions (Mt C/yr^{-1}). Data from EIA (2005). Each arrow shows the sequence from 1980 to 2003 for a country. Note that carbon emissions per unit GDP decelerate as a country gains wealth. The lines in the figure show the slopes associated with the different ratios of GDP and emissions growth (the y-intercepts of the dotted and dashed lines are not important; we moved the lines representing different ratios of GDP and emissions growth to higher y-intercepts so as not to obscure the data summarized by the arrows).



(a)



(b)



(c)

Fig. 3-3. (a) 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 (red 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). (b) Historical U.S. GDP divided among the manufacturing, services, and agricultural sectors. *Source*: Mitchell (1998), WRI (2005). (c) Historical U.S. carbon emissions divided among the residential, services, manufacturing, and transportation sectors. *Source*: EIA (2005).

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 (Fig. 3-2). 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).

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. 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 better agreement. 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).

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)

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 fee; (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 fee 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 CO_2 and 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

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.

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 electricity and hydrogen become the major energy carriers. They are 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.

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

- efficiency improvement,

[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.

- 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 directly or indirectly.[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.

[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 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, 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, use wood waste and sawdust as fuel. Ethanol, currently produced mainly from corn, is blended with gasoline. The CO_2 emission reduction achieved depends on whether the biomass used is replaced, on the fossil-fuel energy used to produce the fuel, and the carbon content of the fuel displaced.

Carbon-free energy sources include hydro,[7] wind, solar, biomass, geothermal, and nuclear fission. 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.

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.

[7] Reservoirs for hydroelectric generation produce CO_2 and methane emissions, so such sources are not totally carbon free.

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 molecules 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.[8] 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 to safely and cost effectively integrate 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 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 and used as an energy source. Methane emissions also occur during production of coal, oil, and natural gas. Such emissions usually can be flared (though this generates CO_2) or collected for use as an energy source. 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.

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

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, 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 the soil type. 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.[9] 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.

INTEGRATED COMPARISON OF OPTIONS

As is clear from the previous sections, there are thousands of options to reduce emissions of or to sequester CO_2. To help them decide which options to implement, policy makers need to know which 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 on other measures as well, 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.

[9]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%.

Changes to the age structure of the population, increases in per capita incomes, and other factors can affect the potential for some options as well. 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 near 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 standardized to a common unit of measurement—2004 U.S. dollars per metric ton of carbon.[10]

Table 4-1. Standardized cost estimates [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. So the estimated scale of

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

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 mitigation 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 individual chapters, along with some estimates of their effects 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 a permit 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 Annex I (industrialized countries only) case for the U.S. economy.

The task of choosing the "best" combination of options may seem daunting given the numerous options and the associated cost ranges. This combination will depend on several factors including the emission target, the emitters covered, the compliance period, and the ancillary benefits 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 permit trading, that cover a large number of emitters and allow them to choose the lowest cost reduction options.

POLICY OPTIONS

Overview

Stabilizing the carbon cycle will require very substantial reductions and increased sequestration of CO_2 emissions. 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. Policies will also need to encourage research and development of technologies that can reduce emissions even further in the long term.

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). A portfolio of options will need to be implemented, including greater efficiency in the production and use of energy; expanded use of renewable energy technologies; technologies for removing carbon from fossil fuels and sequestering it in geological formations; various changes in forestry, agricultural, and land use practices; and possibly other approaches, some of which are currently very controversial, such as nuclear power and certain types of "geoengineering."

Because CO_2 has a long atmospheric residence time,[11] immediate action to reduce emissions and increase sequestration allows its atmospheric concentration to be stabilized at a lower level.[12] 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.

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). Information and voluntary programs are generally not environmentally effective[13] (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 emissions trading system 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.

[11] 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)

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

[13] 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).

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

The choice of policy instrument needs to consider 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, and employment, or in more technical measures of economic well-being (e.g., "welfare measures" such as "compensating variation"). 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.[14] The cost can have competitiveness impacts if some emitters in other jurisdictions are not subject to similar policies. But the societal benefits, such as improved public health and reduced environmental damage, may exceed 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).[15] 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.[16] A policy that raises revenue

[14]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.

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

[16]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.

(an emissions tax or auctioned allowances) has a lower macroeconomic cost than a policy that does not, if the revenue is used to reduce existing distortionary taxes 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.

CO_2 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.

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).[17] In some cases, such as refrigerators, standards have been used successfully to drive technology development.

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 carbon uptake. Policies that affect crop choice (support payments, crop insurance, disaster relief) and

[17]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.

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. The tradable credits can be sold to sources subject to a CO_2 emissions trading program or offset requirement.[18] 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);
- 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). 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 help are needed to create a market for less 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

[18] 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). Also, forests could create carbon offset credits that could be exchanged in tradable carbon systems. Some offset credits might be viewed as temporary. However, there are many circumstances where temporary credits would be valuable additions to a carbon reduction portfolio.

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.[19]

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;
- 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.

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 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 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.

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

[19] 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.

- Encourage adoption of cost-effective emission reduction and sink enhancement measures. An emissions trading program or emission fee 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.
- Adopt appropriate regulations to complement the emissions trading program or emission fee 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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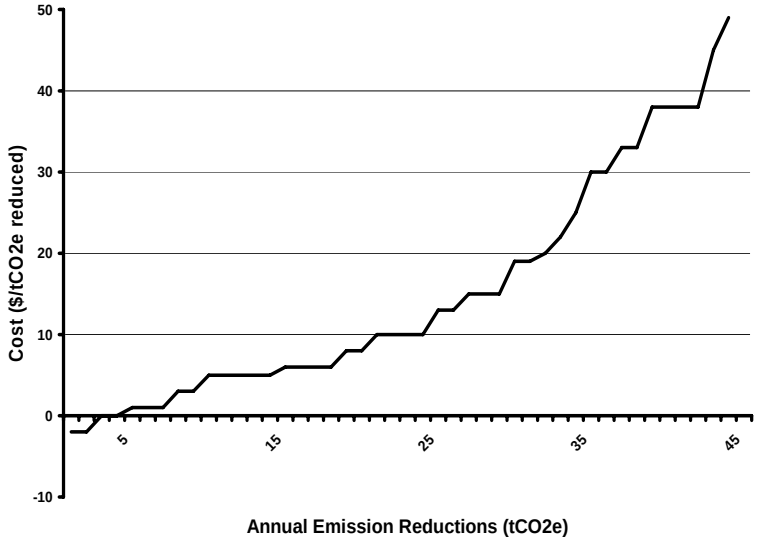
Emission Reduction Supply Curve

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.



Hypothetical emission reduction supply curve.

The curve shows the estimated unit cost ($/t CO_2e) and annual emission reduction (t CO_2e) 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 [annualized cost in 2004 constant U.S. dollars per metric ton of carbon (t C)]

Option/applicable date(s)	Annualized 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	Marginal cost	EMF (2000)
Annex I trading	$19 to 299/t C	Marginal cost	EMF (2000)
Global trading	$7 to 164/t C	Marginal cost	EMF (2000)

Chapter 5. How Can We Improve the Application of Scientific Information to Decision Support Related to Carbon Management and Climate Decision-Making?

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KEY FINDINGS

- Information is lacking on emerging needs and demands for carbon cycle related data and analyses across scales and sectors. In fact, carbon management is a relatively new concept for most decision-makers and members of the public.
- Improving the usefulness of carbon science in North America will require more explicit commitments to generate decision-relevant information.
- Research on the production of policy-relevant scientific information suggests a number of options, from co-production of knowledge to uses of modeling tools in decision support structures and certain uses of "boundary organizations."
- A number of initiatives to improve understandings 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).
- Further participatory pilot experiments should be considered to enhance interactions between climate change scientists and parties involved in carbon management activities and decisions.

INTRODUCTION: THE CHALLENGE OF "USABLE" CARBON SCIENCE

Humans have been inadvertently altering the Earth's carbon cycle since at least the dawn of agriculture, and more rapidly since the industrial revolution. Recent climate science has shown that these influences are large enough to cause significant climate change (IPCC, 2001). In response, environmental

advocates, business executives, and policy-makers have increasingly recognized the need for deliberate management of the carbon cycle. Effective carbon management would seem to require that relevant, appropriate science be communicated to the wide variety of people whose decisions affect carbon cycling. Yet, thus far, carbon cycle science has rarely been organized or conducted in ways that directly support decision making on managing carbon emissions, sequestration, and impacts. There are two main reasons: (1) carbon cycle science has been conducted primarily as basic science[1] and (2) non-scientists have only recently begun to demand carbon cycle information for decision making. As a result, the emerging efforts to consciously manage carbon occur in the virtual absence of information and insights on whether these efforts are appropriate, sufficient, or implemented effectively relative to the needs to reduce carbon emissions and atmospheric concentrations (Dilling *et al*., 2003). To make carbon cycle science more relevant to public and private decision makers, scientists and decision makers will need to clarify what information is most needed 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 short, they will need to collaborate to make carbon cycle science and analysis more "usable" (Mitchell *et al*., forthcoming; Cash *et al*., 2003). Such a component of more "applied" or "solutions-oriented" research could be combined with a basic science portfolio to 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?

The first question to address then is what might we consider "decision support?" There are many different uses of the term. We adopt the definition of decision support included in the U.S. Climate Change Science Program (CCSP) Strategic Plan: "Decision support resources refers to 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? Most people constantly if 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 in these sectors to begin

[1] Carbon cycle research has been applied to agricultural soil management for a number of years; however, the focus has been on improving agricultural productivity, not limiting carbon concentrations in the atmosphere.

making more conscious choices to limit carbon emissions.[2] Whether driven by normative commitments to averting climate change, by political pressures or requirements to reduce carbon emissions, or by economic opportunities and consumer pressures, actors in these sectors are beginning to seek out information that can help them achieve their specific carbon-related goals, including those that relate to or affect the carbon cycle and the climate.[3] Even in countries and economic sectors where no consensus exists on the need to manage carbon, some entities have begun to experiment with carbon-limiting practices and investments in anticipation of a carbon-constrained future.

As part of the process of 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 needs of these stakeholders for information and decision support capabilities, a preliminary review of their interests and activities suggests that there are many stakeholders potentially 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 delineated needs for applied research (Government of Canada, 2005). A few prominent stakeholders in the U.S. are actively using carbon science to move forward with voluntary emissions offset programs such as the Chicago Climate Exchange, which brokers, among other mechanisms, agricultural carbon credits in partnership with the Iowa Farm Bureau.[4] Cities and states, including large regional partnerships on the east and west coasts, are beginning to show interest in managing emissions and carbon-related science (Text Box 1). In addition to these select visible, active stakeholders for carbon-related information, there may be many other potential stakeholders in the U.S. across sectors and scales (Text Box 1). Whether or not interest in carbon information emerges broadly in these constituencies may well depend on whether and how mandatory policies involving carbon management evolve, and what incentives might be put in place. In Europe, for example, mandatory carbon emissions policies have resulted in intense interest in carbon science from interested stakeholders who are directly affected by such policies (Schröter *et al*., 2005).

[2] For examples, see Text Box 1

[3] 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/]

[4] www.iowafarmbureau.com/special/carbon/default.aspx

In the U.S., the federal carbon science enterprise does not have many mechanisms to assess emerging demands for carbon information across scales and sectors. Thus far, federally-funded carbon science has focused predominantly on basic research in order to elucidate some of the fundamental uncertainties in the global carbon cycle and local and regional processes affecting the exchange of carbon (Dilling, in review). Most of the effort at the U.S. federal level is organized under the Climate Change Science Program (CCSP). Almost two-thirds of this effort is managed by the National Aeronautics and Space Administration and the National Science Foundation, whose missions are explicitly focused on basic research, not decision support per se (U.S. Climate Change Science Program, 2006; Dilling, in review). There are research efforts at a relatively lower level of investment at the Department of Energy and the U.S. Department of Agriculture under the CCSP[5] 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 between these programs may enhance the ability of CCSP carbon-related research to serve decision support needs.

Until perhaps the past decade, carbon management as a concept was not widely recognized—even now, most members of the public do not know the term "carbon sequestration" or understand its potential implications (Shackley *et al*., 2005; Curry *et al*., 2004). In more recent years, however, the carbon cycle science community has increasingly recognized that it may have more direct relevance to issues of policy and decision making, calling for "coordinated rigorous, interdisciplinary research that is strategically prioritized to address societal needs" (Sarmiento and Wofsy, 1999). The North American Carbon Program's (NACP) "Implementation Plan" lists decision support as one of four organizing questions (Denning *et al*., 2005).

As stated in that same plan, however, little is known in the scientific community about the likely users of decision support information that might emerge from a program such as the NACP. 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).

There are two programs within the CCSP framework that may inform this question of how to link carbon science to user needs more explicitly in the coming years. NASA has an Applications program

[5] 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.

that seeks to find uses for its data and modeling products using a "benchmarking systems" approach, and USDA and DOE have invested significant resources in science that might inform future carbon sequestration efforts and carbon accounting in agriculture and forests. Conducted as separate efforts, the programs have not yet been integrated into a broader framework aimed at making carbon cycle science more useful to decision makers within the CCSP carbon research agenda, but certainly may contribute to such a strategy if developed.

Improving the usefulness of carbon science in North America will require more explicit commitments by scientific research 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 may be helpful both in refining research agendas and accelerating 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 that have examined the creation and use of knowledge for decision making have found that information 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 decision makers believe is fair, unbiased and respectful of divergent views and interests) (Mitchell *et al*., forthcoming; Cash *et al*., 2003). Even the most technically and intellectually rigorous science may fail to influence decision makers if it does not address the decisions they face, or if it is conducted in a way that they perceive as biased or unresponsive to their concerns.

Research on the production of policy-relevant scientific information suggests strategies to maintain the integrity of the research endeavor while increasing its policy relevance. Although communicating results more effectively is important, generating science that is more applicable to decision making may require modifying the way scientific information is produced. Carbon cycle scientists and carbon decision makers will need to develop methods for interaction that work best in their specific application. At their core, all of these strategies promote scientist-stakeholder interaction 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*., forthcoming). Such processes work best when they enhance the research and its utility while preserving the credibility of both scientists and stakeholders. Transparency and 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 nine regional partnerships across the U.S., university researchers partner with local operational agencies and others that might incorporate climate information in decision making. New research is developed in consultation with all partners in an ongoing, iterative process (Lemos and Morehouse, 2005).
- *Institutional experimentation and adaptive behavior* (*e.g., adaptive management)*: Adaptive management is a powerful concept that acknowledges the inherent uncertainty of responses of natural systems to human management, and seeks to periodically assess the outcomes of management decisions and adjust policy decisions and new actions accordingly, a form of deliberate "learning by doing" (c.f. Holling 1978). Adaptive management principles have been applied for resources with multiple interests at stake, such as management of large river systems as well as forests in the Pacific Northwest (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, salient and legitimate played a significant role in the successful implementation of the Montreal Protocol which phased out the use of ozone-depleting substances. The presence of a highly credible scientific and technical assessment process with diverse participation from academics and industry scientists is credited as a key factor in the Protocol's success (Parson, 2003).
- *Mediated modeling*: Shared tools can facilitate scientist-user interactions, help diverse groups orient around a problem and illuminate common assumptions as well as differences. Mediated modeling involves a guided process in which participants from a wide variety of perspectives jointly construct a computer model that can be used in solving complex environmental problems, or envisioning a shared future. The process has been successfully used for watershed management, endangered species management and a host of other difficult environmental issues (Van den Belt, 2004).
- *Carbon modeling tools as decision support*: As carbon management within the United States is increasingly considered at the national level, some federal agencies have begun to develop decision support tools to help estimate carbon sequestration in various ecosystems and under various land use scenarios. These pilot-phase tools are available online and feature a customizable user interface (see examples such as the NASA Ames CQUEST, Carbon Query and Evaluation Support Tools, http://geo.arc.nasa.gov/website/cquestwebsite/; the U.S. Forest Service COLE, Carbon Online Estimator, http://ncasi.uml.edu/COLE/; and Colorado State COMET-VR, CarbOn Management Evaluation Tool, http://www.cometvr.colostate.edu/).

Over time, well-structured scientist-stakeholder interaction can bring substantial benefits to both scientists and decision makers (Moser, 2005). Scientists learn to identify research questions that are both scientifically interesting and relevant to decisions, and to frame their answers in ways that audiences are more likely to find compelling. Non-scientists learn more about what questions science can and cannot answer. They also 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).

Such interactive approaches to research also 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 consumes considerable time and effort. Involving private sector firms may require scientists accustomed to working in an open informational environment to navigate in a world in which much information is proprietary. Scientists may also choose not to pursue 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).

On the stakeholder side, some may lack the financial resources, expertise, time, and other capacities needed for meaningful participation. Some will distrust scientists in general and government-sponsored science in particular due to cultural, institutional, historical, or other factors. Some may reject participation in open and public processes in which they must interact with those with whom they disagree politically or compete economically. In some cases, stakeholders will try to manipulate research questions and findings to serve their political or economic interests. Perhaps most importantly, stakeholders often show little interest in diverting their time (or that of their employees) 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 exist to a large extent as quite separate social and professional realms, with quite different traditions, norms, codes of behavior, and reward systems. The boundaries that exist between them serve many useful functions but may also inhibit the transfer of useful knowledge across those boundaries. According to Guston (2001), a boundary organization is an institution that “straddles the shifting divide” between politics and science. Boundary

organizations are accountable to both sides of the boundary and involve professionals from each, as well as those serving in a mediating role. Such "boundary spanning" individuals and organizations can often facilitate the uptake of science by translating scientific findings so that stakeholders find them more user-friendly and by stimulating adjustments in research agendas and approach. Boundary organizations can exist at a variety of scales and for a wide variety of purposes. Cooperative agricultural extension services and NGOs that successfully convert large-scale scientific understandings of weather, aquifers, or pesticides into locally-tuned guidance to farmers are classic examples of boundary organizations (Cash, 2001). The International Research Institute for Climate Prediction focuses on seasonal-to-interannual scale climate research and modeling so that their research results are useful to farmers, fishermen, and public health officials (e.g., Agrawala *et al*., 2001). The Subsidiary Body for Scientific and Technological Advice (SBSTA) of the United Nations Framework Convention on Climate Change serves also as a boundary organization at an international level. The SBSTA serves as a link between information and assessments provided by expert sources (such as the IPCC) and the Conference of the Parties (COP), which focuses on setting policy.[6] The University of California Berkeley Digital Library Project Calflora project has sought to ensure that an extensive database on plants is designed and implemented in ways that support environmental planning (Van House *et al*., 2003).

And of course, there are other significant challenges to the use of knowledge, even when created through self-conscious efforts like those just delineated. People fail to integrate new research and information in their decisions for many reasons. Besides obstacles already mentioned, people often are not motivated to use information that implies or 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 that it gets used but it will make it possible and more likely that it will.

RESEARCH NEEDS TO ENHANCE DECISION SUPPORT FOR CARBON MANAGEMENT

There is likely to be substantial and growing demand for detailed analysis of carbon management issues and options across major economic sectors, nations and levels of government in North America. This is especially likely in jurisdictions that place policy constraints on carbon budgets, such as within the states comprising the Regional Greenhouse Gas Initiative, or the State of California. Although some new

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

efforts are underway in parts of agencies, carbon cycle science, at least in the U.S., could be organized and carried out in ways that better meet this potential demand in a more systematic fashion. As noted by the National Research Council (2004), effective implementation of the goals of the program, as a part of the Climate Change Science Program, "requires focused research to develop decision support resources and methods." While such recommendations were stated for the whole of the program, they are pertinent to carbon-related science as one of the major components.

The process of creating information to support decision making should be significantly different from the process of creating "basic" or "fundamental" scientific knowledge. The primary driver for such "use-inspired" research is societal need, not scientific curiosity alone (Stokes, 1997). To improve the application of scientific information to support carbon and climate-related decisions, scientists and non-scientist carbon managers need to improve their joint understanding of the top priority questions facing carbon-related decision making. They also need to collaborate more effectively in undertaking research and interpreting results in order to answer those questions. The scale of information provided and its specificity to regional or local concerns are often important considerations for the salience of information (Cash and Moser, 2000).

As a first step, a formal process could be developed "for gathering requirements and understanding the problems for which research can inform decision makers outside the scientific community," including the formation of a decision support working group (Denning *et al*., 2005). To move forward on creating an effective decision component of the CCSP program, the NRC recommends organizing a variety of deliberative activities, such as workshops, focus groups, working panels, and citizen advisory groups, with the goals being 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). The current status of decision support activities across the CCSP will be assessed by several other SAP processes, complementary to this one, specifically SAP 5.1, 5.2, and 5.3 (organized under the heading of "Explore the uses and identify the limits of evolving knowledge to manage risks and opportunities related to climate variability and change").

SUMMARY AND CONCLUSIONS

The carbon cycle is influenced through deliberate and inadvertent decisions on the part of diverse and spatially dispersed actors, located in many different sectors and at different scales. Scientific information and analysis can lead to better-informed decision making across many sectors and levels of action, if decision makers recognize that information and analysis as relevant and legitimate. To make carbon cycle

science more useful to decision makers, we suggest the following steps, to be initiated by leaders in the scientific and program level carbon science community:

- 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 and communication experts.
- 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 not an exhaustive list nor is it based on a rigorous assessment, it is meant to demonstrate the wide variety of potential stakeholders with an 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 demonstrated significant interest in carbon management as ways 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 non-profits might 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 on 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: 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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