





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

November 2007

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The North American Carbon Budget and Implications for the Global Carbon Cycle

Synthesis and Assessment Product 2.2
Report by the U.S. Climate Change Science Program
and the Subcommittee on Global Change Research

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November 2007

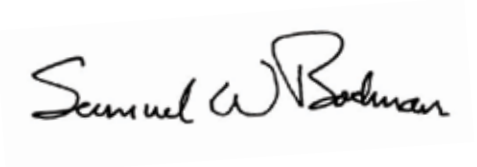
Members of Congress:

On behalf of the National Science and Technology Council, the U.S. Climate Change Science Program (CCSP) is pleased to transmit to the President and the Congress this report, *North American Carbon Budget and Implications for the Global Carbon Cycle*, as part of a series of Synthesis and Assessment Products produced by the CCSP. This series of 21 reports is aimed at providing current evaluations of climate change science to inform public debate, policy, and operational decisions. These reports are also intended to inform CCSP's consideration of future program priorities.

CCSP's guiding vision is to provide the Nation and the global community with the science-based knowledge to manage the risks and opportunities of change in the climate and related environmental systems. The Synthesis and Assessment Products are important steps toward that vision, helping translate CCSP's extensive observational and research base into informational tools directly addressing key questions that are being asked of the research community.

This product will contribute to and enhance the understanding of the North American carbon budget and the implications for the global carbon cycle. It was developed with broad scientific input and in accordance with the Guidelines for Producing CCSP Synthesis and Assessment Products, Section 515 of the Treasury and General Government Appropriations Act for Fiscal Year 2001 (Public Law 106-554), and the Information Quality Act guidelines issued by the Department of Commerce and the National Oceanic and Atmospheric Administration pursuant to Section 515.

We commend the report's authors for both the thorough nature of their work and their adherence to an inclusive review process.



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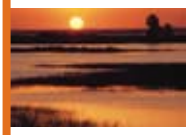

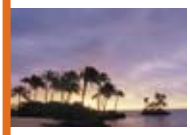

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ABSTRACT

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

There are also globally important carbon sinks in North America. In 2003, growing vegetation in North America removed approximately 500 million tons of carbon per year (± 50%) from the atmosphere and stored it as plant material and soil organic matter. This land sink is equivalent to approximately 30% of the fossil-fuel emissions from North America. The imbalance between the fossil-fuel source and the sink on land is a net release to the atmosphere of 1350 million metric tons of carbon per year (± 25%).

Approximately 50% of North America's terrestrial sink is due to the regrowth of forests in the United States on former agricultural land that was last cultivated decades ago, and on timberland recovering from harvest. Other sinks are relatively small and not well quantified with uncertainties of 100% or more. The future of the North American terrestrial sink is also highly uncertain. The contribution of forest regrowth is expected to decline as the maturing forests grow more slowly and take up less carbon dioxide from the atmosphere. But, how regrowing forests and other sinks will respond to changes in climate and carbon dioxide concentration in the atmosphere is highly uncertain.

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

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PREFACE

Report Motivation and Guidance for Using This Synthesis/Assessment Report

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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 (SAPs) that address its highest priority research, observation, and decision support needs.

This report—CCSP SAP 2.2—addresses Goal 2 of the CCSP Strategic Plan: Improve quantification of the forces bringing about changes in the Earth's climate and related systems. The report 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 North America and the rest of the world, and (2) provides scientific information for decision support focused on key issues for carbon management and policy. Consequently, this report is aimed at both the decision-maker audience and to the expert scientific and stakeholder communities.

Background

This report addresses carbon emissions; natural reservoirs and sequestration (absorption and storage); 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 coastal oceans, where "North America" is defined as Canada, the United States of America (excluding Hawaii), and Mexico. Coastal oceans are defined as coastal waters less than 100 km from the North American coastline, where surface water concentrations of carbon dioxide (CO_2) are influenced by coastal processes. The report focuses on the current carbon budget for North America defined by the availability of most recent published data circa 2003. Historical trends and processes from 1750 (beginning of the Industrial Revolution) and 1850 (expanding use of fossil fuels in the Industrial Revolution) to present are included where appropriate and needed to explain the current carbon budget. Near term (to 2020), mid term (2020-2040), and long-term (2040-2100) projections of current trends are considered where available (published) and appropriate. 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) www.nacarbon.org/nacp/about.html can be compared.

The focus of this report follows the *Prospectus* developed by the Climate Change Science Program and posted on its website at www.climatescience.gov. The audience for SAP 2.2 includes scientists, decision makers in the public sector (*e.g.*, national, provincial, state, and local governments), the private sector (carbon-related industry, including energy, transportation, agriculture, and forestry sectors; and

[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*.

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 SAP, 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 the state of knowledge concerning carbon cycling and the carbon budget of North America.

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 North America 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 North America; and (5) to inform future efforts for carbon science to support decision making. For example, well-quantified regional and continental-scale carbon source and sink estimates, error terms, and associated uncertainties will be available for use in 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 North America's role in the global 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 CO_2 or other changes in the carbon cycle on the land and oceans of North America?
- What options can be 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 CO_2)?
- How can we improve the usefulness of carbon science for decision making?
- What additional knowledge is needed for effective carbon management?

Suggestions for Reading, Using, and Navigating This Report

The above questions provide the basis for the five chapters in Part I of this SAP. These five chapters focus on integrating and synthesizing information presented in Parts II and III of this report in combination with additional peer-reviewed published information from outside the report. The report's assessment of the North American carbon budget is, for example, presented in Chapter 3. The *Executive Summary* further distills and synthesizes information from across the report to address the questions above, which structure the report.

Part II of the report focuses on the energy- and industrial-related components of the North American carbon cycle and discusses the carbon emissions and other 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. Both Parts II and III are introduced by an *Overview* of the subject matter and information in the chapters of the respective sections.

A reader interested in cross-sector integration and synthesis at the national and continental scale might, therefore, first read the *Executive Summary* followed by reading Chapters 1 through 5, referring to Chapters 6-15 and the *Overviews* of Parts II and III for more expanded discussion of information specific to individual sectors or ecosystems. Conversely, if a reader is more interested in sectoral-specific information, he or she might want to peruse the appropriate chapters in Part II as a first step. Chapter 1 is intended as a background "primer" for those less familiar with concepts of carbon cycling and its importance in considerations of climate change. Those familiar with those issues might choose to skip that chapter or use it for a quick review.

Definitions and Conventions

Throughout this report, quantification of carbon sources and sinks follows the following convention. *Sources*, such as fossil-fuel emissions, that add carbon to the atmosphere are indicated with positive numbers. *Sinks*, such as forest growth, that remove carbon from the atmosphere are indicated with negative numbers. The difference between a source and a sink is *net* exchange with the atmosphere, and may be either positive or negative (*i.e.*, a source or sink), depending on which is larger. Sources and sinks, unless otherwise indicated, are given in units of million metric

tons of carbon per year (Mt C per year).

Additional definitions of terms, acronyms, and units are provided in the *Glossary and Acronyms* section of this report.

The Treatment of Uncertainty in This Report

Communicating confidence in the findings of scientific syntheses and assessments, including the characterization of certainty in numbers reported by those assessments, is an important part of making scientific assessments useful to decision makers and other stakeholders. That communication is sometimes challenged by nuanced differences among participants in their understanding of terms such as uncertainty or confidence. The challenge is heightened when attempting to integrate and synthesize analyses from a broad spectrum of sectors and disciplines, each with its own methods, conventions, and sometimes language for addressing and communicating "uncertainty."

Variability in physical processes (*e.g.*, carbon sequestration by woody vegetation) in time and space, measurement error, and sampling error (itself intimately linked to temporal and spatial variability) all contribute to uncertainty in quantifying elements of the North American carbon budget. Uncertainties may be compounded by the use of "expansion factors"—the analytical models used to interpolate and extrapolate local measurements to represent larger areas. Methods for translating from the readily measurable to quantities that are difficult or costly to measure (such as the use of allometric relationships to estimate whole tree biomass from measurements of stem diameter and tree height) can also compound uncertainty. The magnitudes of these and other sources of uncertainty vary across sectors and elements of the carbon cycle. Consequently, so do the emphases and methods for dealing with uncertainty vary across the different disciplines that study these elements. There is no single applicable quantitative method for integrating these variable sources and methods. There exist, of course, statistical techniques, such as the meta-analysis widely used in epidemiology and biomedical clinical trials to combine results from previous separate but related studies. But only rarely, even within a sector or discipline, are the statistical pre-requisites of meta-analysis met by the diverse studies of carbon cycle elements.

To address this challenge, and to provide for synthesis across and comparability among carbon cycle elements, a convention has been adopted for characterizing uncertainty in the report's synthetic findings and results (for example, in the synthesized carbon budget for North America of Chapter 3 and in the Executive Summary). Uncertainty is characterized using asterisks to represent the five categories described in the accompanying text box.

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

These are informed categorizations. They reflect expert judgment, using all known published descriptions of uncertainty surrounding the "best available" or "most likely" estimate. There is always a chance, something like 1 in 20, that the actual value lies outside the range surrounding the best/most likely estimate, but it is much more likely that the actual value is in that range. Some things are known well, and one can be highly (95%) certain that the actual value is within ± 10% of the estimate. Some things are known less well, perhaps there are fewer studies, a broader, more variable range of estimates from different studies, or more variability or measurement and sampling error reported by individual studies, and one can only be highly certain that the actual value is captured by the estimate by increasing the relative range around the estimate to say ± 25 or 50%. With very few and variable or conflicting studies, there is very little certainty and confidence in the estimate, the relative range of likely values is large and uncertainty is characterized as being greater than 100%.

CCSP SAP 2.2 Uncertainty Conventions

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

The 95% boundary was chosen to communicate the extremely high certainty or confidence that the actual value was in the reported range, and the low likelihood that it was outside that range. However, this characterization is not a statistical property of the estimate, and should not be confused with 95% confidence intervals based

on parametric statistical estimation of the standard error of the mean.

The authors have used this system for categorizing uncertainty only where they have synthesized diverse published information and compared across this diversity. When citing an existing published estimate, authors were encouraged to include the reported characterizations of uncertainty, whether quantitative or qualitative. Chapters in this report, especially those of Parts II and III, therefore, include several different ways of characterizing uncertainty: simple ranges, standard deviations, standard error, and confidence intervals.

In all cases, the form and character of the uncertainty being expressed should be clear either from the context of the text or as described in a footnote. There are circumstances in which no characterization of the uncertainty of data or information is shown, such as when a number is taken from a published source that itself did not include a characterization of uncertainty. In these cases, the authors have not provided a characterization of uncertainty, and the reader should assume that no characterization of uncertainty was available to the authors.

The Treatment of Greenhouse Gases in This Report

Atmospheric CO_2 is recognized as the largest single human-mediated agent of climate change. While CO_2's importance as a greenhouse gas is a primary motivator for understanding how carbon cycles through the atmosphere and other parts of the Earth system, this report is about the carbon cycle and carbon budgets, and not about greenhouse gases. Accordingly, this report focuses on the North American carbon budget as it influences, and is influenced by, concentrations of atmospheric CO_2. Methane (CH_4) is also an important greenhouse gas and a potential contributor to human-caused climate change. However, CH_4 and other non-CO_2 carbon gases are not typically included in global carbon budgets because their sources and sinks are not well understood. For this reason, and to manage scope and focus, we too follow that convention, and this report is limited primarily to carbon and CO_2. There is significant discussion of CH_4 in individual chapters where appropriate (*e.g.*, Chapter 8 on industry and waste management, Chapter 10 on agricultural and grazing lands, and Chapter 13 on wetlands), but the report's coverage of CH_4 is not comprehensive. We made no effort towards an across-sector, continental-scale synthesis and assessment of CH_4 as part of the North American carbon budget. Similarly, we provide no comprehensive treatment of black carbon, isoprene, or other volatile organic carbon compounds that represent a small fraction of global or continental carbon budgets. We make no consideration of nitrous oxide (N_2O) or other non-carbon greenhouse gases.

The Treatment of Emissions Data Sources in This Report

Part II of this report (Chapters 6 through 9) discusses patterns and trends of CO_2 emissions by sector (the transportation sector, for example). Estimating emissions by sector brings special challenges in defining sectors and assembling the requisite data. Readers will find that there is consistency and coherence within each of the report's chapters but will encounter differences across chapters. Different experts and different disciplines with different perspectives on the carbon cycle use different sector boundaries, different data sources, different conversion factors, *etc.* Different analysts and literature sources will use data for different base years and may treat, for example, electricity and biomass fuels differently. The national reports of the United States, Canada, and Mexico do not cover the same time periods nor do they present data in the same way. In this report, the chapter authors have chosen the system boundaries and data they find most useful for their sectors and perspectives, even though it makes for some differences across chapters. However, the database of the International Energy Agency (IEA; www.iea.org) allows for summary of CO_2 emissions for the three countries defined as North America in this report according to sectors that closely correspond to the sectoral division of Chapters 6 through 9 (See the Part II Overview). Similarly, the database of the Energy Information Administration (EIA; www.eia.doe.gov) provides total global and North American fossil-fuel emissions (by country) as a reference against which the relative size and contribution of sector emissions and carbon sinks can be compared (Chapters 2 and 3).

The Synthesis and Assessment Product Team

A full list of the Authorship Team (in addition to the list of lead authors provided at the beginning of each chapter) is provided on page iv of this report. The Scientific Coordination Team, as described below, reviewed the scientific/tech-

nical input and managed the formatting, editing, assembly, and preparation of the report.

The SAP 2.2 *Prospectus* identified a Scientific Coordination Team responsible for organizing and outlining this SAP and for its final content and submission. The Coordination Team was also responsible for identifying chapter authors, coordinating all of the inputs to this report, and leading the overall synthesis and integration of this report. The Coordination Team provided oversight and editorial review of individual chapters and, with the assistance of the respective chapter authors, prepared the *Part II Overview* and *Part III Overview*, as well as the *Abstract* and the *Executive Summary* for this report. The "Key Findings" accompanying Chapters 2–15 were developed in collaboration between the Scientific Coordination Team and the respective chapter authors. These findings were compiled and edited for length, style, and consistency by the Coordination Team as part of the synthesis and integration across the report. Therefore, any error or misrepresentation in the "Key Findings" is the responsibility of the Scientific Coordination Team, and not of the chapter authors.

The members of the Coordination Team and their roles are:

- Dr. Anthony W. King, Overall Lead
- Dr. Lisa Dilling, Co-Lead, Stakeholder Interaction Lead
- Dr. David M. Fairman, Stakeholder Interaction
- Dr. Richard A. Houghton, Scientific Content (Land Use)
- Dr. Gregg Marland, Scientific Content (Emissions)
- Dr. Adam Z. Rose, Scientific Content (Economics)
- Dr. Thomas J. Wilbanks, Scientific Content (Human Dimensions)

The activities of the Scientific Coordination Team were managed by:

- Mr. Gregory P. Zimmerman, Project Coordinator

The Scientific Coordination Team recruited one or more scientific experts to be responsible for writing each individual chapter of SAP 2.2. This person (or persons) was designated as either the Coordinating Lead author or the Lead Chapter author. For the individual chapters in Part I, the respective Coordinating Lead author had responsibility for orchestrating the preparation of the chapter. For each chapter in Parts II and III, the respective Lead Author had that responsibility. These Coordinating Lead authors and Lead Chapter authors are recognized leaders in their fields, drawn from the wide and diverse scientific community of North America and the world, as well as other qualified stakeholder groups. Their qualifications include the quality and relevance of current publications in the peer-reviewed literature pertaining to their chapter topics, past or present positions of leadership in the topic fields, and other documented experience and knowledge of high relevance. Each Coordinating Lead author and Lead Chapter author was responsible for the review and synthesis of current knowledge and production of text for his/her respective chapter. The Coordinating Lead authors and Lead Chapter Authors were responsible for recruiting well-qualified contributing authors in their areas of expertise and responsibility. The Coordinating Lead authors and Lead Chapter Authors, along with the Scientific Coordination Team, were also responsible for ensuring that scientific expert, stakeholder, and public review comments on their chapters are reflected in this report.

Stakeholder Involvement Process

Research suggests that in order for an assessment to be useful for decision making, it must be not only scientifically accurate and rigorous, but also relevant to the near-term concerns of decision makers and their constituencies ("stakeholders"). It must also be created in a way that stakeholders perceive as fair and unbiased; this last point is especially important when the assessment deals with a controversial public issue.

To make the SAP 2.2 as useful for decision making as possible, we dedicated significant effort and resources to developing a stakeholder engagement process. Because the North American carbon cycle involves a vast array of interactions between human activities and the environment, and because changes in the carbon cycle may have far-reaching economic, social, and political implications, the stakeholders for this report arguably include the entire population of the continent.

To focus the stakeholder engagement process, the Coordination Team sought to identify and involve representatives of government (national and subnational) with current or potential responsibility for carbon management, businesses with a substantial interest in carbon management, and environmental groups active in carbon cycle issues, along with academic and consulting experts in carbon cycle issues. We were partially successful in our efforts to involve a broad and representative group of stakeholders. Our extensive outreach efforts generated public comments from only a limited number of individuals, and attendance at our individual workshops was not equally balanced across all stakeholder groups. We did, however, succeed in generating participation and public comment from all the major stakeholder groups. What the process lacked in numbers, it arguably made up for in the quality of interaction and feedback received.

The stakeholder engagement process involved a combination of interviews, workshops, and online communication tools such as a website and email. Stakeholders' interests

were considered and represented at all stages. However, the responsibility for content of the report rested with the authors themselves.

We began involving stakeholders early in the process, at a point where they might have significant opportunity to provide input into the shape and overall structure of the report. Our first activity was to conduct a "rapid stakeholder assessment" which consisted of approximately 30 phone interviews with stakeholders from government, academia, business, and environmental groups. During this assessment, we asked stakeholders about their impressions of our tentative outline for the report, and for suggestions on chapter authors.

We then conducted the first of our stakeholder workshops, also focusing on the draft outline and asking how we might make the report as useful as possible to a wide range of stakeholders. At this workshop, we significantly changed the structure of the report based on valuable input from the group assembled. After the workshop, we then posted our draft outline online, and provided an open comment period for anyone to send in comments, which were also considered in constructing the next draft and formal SAP 2.2 *Prospectus* outline. We also created an online email listserv early in the process, which now has over 350 members subscribed. Our second workshop occurred mid-way through the process, when the authors had created an early draft of their chapters. At the workshop, stakeholders and authors met together, so that input and feedback could be direct and interactive. Through the Climate Change Program Office, we then received feedback on a peer-reviewed draft through a formal public comment process. Finally, we conducted a third stakeholder workshop during the public comment process, in order to have one more opportunity for direct dialogue on the document. We also maintained a public website from the start of the process with our names and contact information, and communicated via email and phone with stakeholders. The website can be accessed at http://cdiac.ornl.gov/SOCCR.