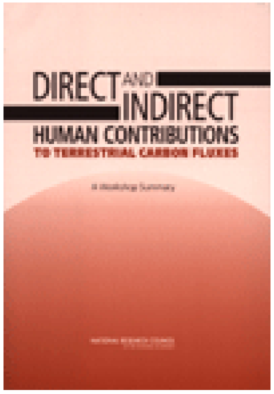

Direct and Indirect Human Contributions to Terrestrial Carbon Fluxes: A Workshop Summary

Rob Coppock and Stephanie Johnson, National Research Council

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DIRECT AND INDIRECT HUMAN CONTRIBUTIONS TO TERRESTRIAL CARBON FLUXES

A Workshop Summary

By Rob Coppock and Stephanie Johnson

Board on Agriculture and Natural Resources

Division on Earth and Life Studies

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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This summary has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We thank the following individuals for their review of this summary: Richard A. Houghton, The Woods Hole Research Center, George Hurtt, University of New Hampshire, James Katzer, ExxonMobil Research and Engineering Company (retired), Dennis Ojima, Colorado State University, Michael J. Prather, University of California, Irvine, and Ron Sass, Rice University

Although the reviewers listed above provided many constructive comments and suggestions, they did not see a final draft of the summary before its release. The review of the summary was overseen by Thomas Graedel of Yale University. Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authors and the institution.

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1

Introduction

Human-induced climate change is an important environmental issue worldwide, as scientific studies increasingly demonstrate that human activities are changing the Earth's climate. For more than 420,000 years the CO_2 abundance in the atmosphere was bounded, oscillating between about 180 and 280 parts per million (ppm) over the glacial and interglacial periods. However, since the Industrial Revolution, the CO_2 abundance has risen to 375 ppm and continues to rise according to the Intergovernmental Panel on Climate Change (IPCC, 2001). Research suggests that most of the observed global warming of the past 50 years, including the increase in atmospheric CO_2, can be attributed to human activities (IPCC, 2001; see Box 1-1). Even if dramatic reductions in emissions were made today, some human-induced changes are likely to persist beyond the 21st century because of the slow response of the climate system caused by the long residence times of many greenhouse gases in the atmosphere, the large heat capacity of the oceans, and the dynamics of other components such as ice sheets and the biosphere. Nevertheless, current research indicates that taking measures to limit CO_2 emissions in the atmosphere can mitigate these impacts (IPCC, 2001). Considerable attention has focused on measures that could be taken by the energy sector, but land use, land use change, and forestry activities have also been proposed as a means of moderating the effects of climate change, either by increasing the removal of greenhouse gases from the atmosphere or by reducing emissions.

BOX 1-1
Background on the Carbon Cycle

William Schlesinger, Duke University, provided an overview of the global carbon cycle to provide background to the discussion of direct and indirect effects on carbon fluxes. The abiotic elements of the carbon cycle include volcanic emissions, carbonate and silicate rock weathering, and air-sea exchange, (see Figure 1-1), although carbon fluxes expand substantially with the addition of biotic processes (see Figure 1-2). For the mid-1990s, Schlesinger noted that the exchange in and out of the terrestrial biota was more than 100 Pg C/yr. Much of this carbon is either respired within the terrestrial biosphere or is emitted by decomposers or fires. A rough balance exists between the natural exchange of terrestrial inputs and outputs of carbon, with only a small amount escaping decomposition and moving into the soil pool.

The human impact on the carbon cycle is twofold. First, humans are converting forests to agricultural lands and thus releasing carbon from forest stands and soil reservoirs, particularly in the tropics. The burning of fossil fuels also serves as a very large source of carbon in the atmosphere. The amount of atmospheric carbon released from fossil fuel emissions is four or five times larger than estimates of carbon emissions from net vegetation destruction. When comparing the sum of these net human-induced atmospheric emissions with estimated carbon sinks, Schlesinger highlighted the residual sink, which illustrates the current incomplete understanding of carbon uptake. The residual sink (previously called the "missing sink") represents the apparent imbalance in global CO_2 accounting:

$$\text{Atmospheric increase} = \text{Fossil fuel emissions} + \text{Net emissions from land use} - \text{Ocean uptake} - \text{Residual sink.}$$

It has been estimated (by difference) at 2.9 Pg C/yr for the 1990s (Houghton, 2003). Robert Watson of the World Bank noted that the residual carbon sink appears to be increasing, up from 1.9 Pg C/yr in the 1980s. Schlesinger proposed several explanations for this residual sink, including carbon accumulation in the undisturbed terrestrial biosphere due to CO_2 fertilization. Forests may also be growing back on previously deforested land or changing their distribution on the landscape in a way that replaces low carbon sinks with high carbon sinks. Research has shown that the Earth's biota have a strong effect on the global carbon cycle through seasonal fluctuations in CO_2 (e.g., Keeling and Whorf, 2004; see Figure 1-3). Because the residual sink is thought to originate from terrestrial processes, the net terrestrial flux can be calculated as follows:

Box 1-1 (continued)

Net terrestrial flux = Net emissions from land use – Residual sink.

Schlesinger stated that the origin of this residual sink has significant implications and opportunities for policy makers. If the sink exists in forested or agricultural land and policy makers are concerned about global warming, the function of that portion of the biosphere (removing CO_2 from the atmosphere) would merit preservation. Schlesinger noted that if this sink were lost, atmospheric CO_2 concentration could rise much faster. However, he noted that a policy intended to absorb much of the nation's emissions, let alone much of the industrialized world's emissions, through land use and forestry would be unrealistic. Schlesinger's rough calculations based on typical sequestration rates suggest that it would take extremely large areas of forest lands (Schlesinger calculated 2.2 million miles^2 or nearly 10 times the area of Texas) to offset annual U.S. carbon emissions.

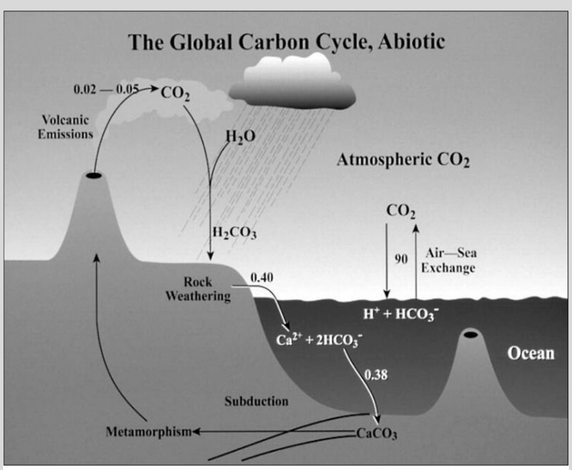

FIGURE 1-1 The global carbon cycle on a lifeless earth. All units in petagrams of carbon per year. Source: Schlesinger (2003)

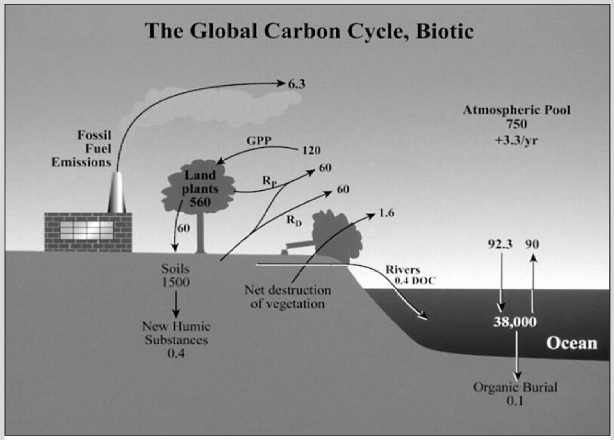

FIGURE 1-2 The global biotic carbon cycle. All units in petagrams of carbon per year. Source: Schlesinger (2003.)

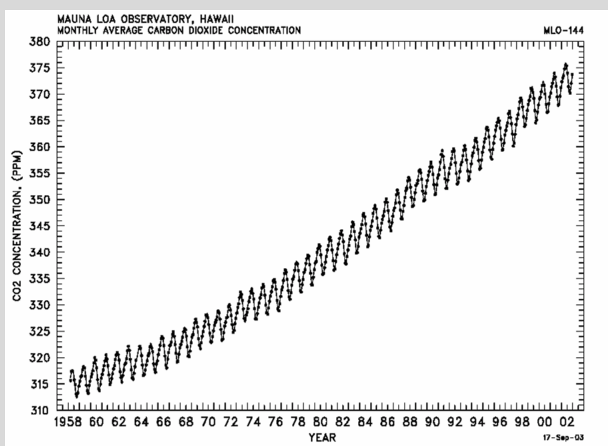

FIGURE 1-3 CO_2 measured at Mauna Loa Observatory. Source: Keeling and Whorf (2004)

DIRECT AND INDIRECT HUMAN-INDUCED EFFECTS ON GREENHOUSE GASES

The United Nations Framework Convention on Climate Change and the Kyoto Protocol (see Box 1-2) both call for emissions reporting that separates human activities directly affecting atmospheric concentrations of greenhouse gases from those caused by indirect and natural factors. Examples of direct influences on greenhouse gas fluxes are the burning of fossil fuels and management actions such as reforestation, agricultural practices, and fire suppression. Examples of indirect influences include CO_2 fertilization, nitrogen deposition, acidic deposition, temperature and precipitation changes, invasive species, and tropospheric ozone. Natural effects on greenhouse gas fluxes could occur due to climate variability, pests, or changes in fire frequency and intensity (not including human efforts at fire suppression).

At the workshop, Christopher Field noted that the main motivation for factoring out direct and indirect effects in any carbon management scheme is to provide credit for something that requires an investment for purposeful action. By separating direct and indirect effects, countries are not punished or provided credit for an accident of nature, such as the fact that a country's forests happen to be sensitive to CO_2 fertilization. Accordingly, countries are not given credit for actions in the past, such as regrowth in a previously harvested forest. The Intergovernmental Panel on Climate Change (2000b) reports that approximately 2.2 petagrams[1] of carbon per year (Pg C/yr) is sequestered globally by terrestrial

BOX 1-2
International Response to Rising Greenhouse Gas Emissions

The international community is addressing the issue of rising greenhouse gas levels through the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol. The UNFCCC articulates the long-term objective as follows: stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous human-induced interference with the climate system, with a specific focus on food security, ecological systems, and sustainable economic development. The Kyoto Protocol aims to supplement and strengthen the UNFCCC by setting legally binding emissions targets and including steps for implementation, accounting, reporting, and review. Specifically, the Kyoto Protocol requires most industrialized countries to reduce emissions by 2012 to 5 to 8 percent below those emitted in 1990. The UNFCC and Kyoto Protocol provide the context for climate change research.

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[1] Petagrams are equivalent to 10^{15}grams or 1 gigaton (Gt).

ecosystems through biomass growth resulting from CO_2 and nutrient fertilization and changing climate and regrowth resulting from natural regeneration.

The definitions of indirect and direct effects were one focus of discussion at the workshop. Although Michael J. Prather emphasized that the definitions of direct and indirect effects are ultimately negotiated by global policy makers and the workshop participants agreed not to debate this, the discussion is presented here to illuminate some of the participants' concerns. For context a recent IPCC discussion of direct and indirect effects is presented in Box 1-3. Indirect human-induced effects were generally considered by workshop participants to result from environmental changes that could affect rates of photosynthesis, respiration, growth, and decay, such as elevated atmospheric CO_2 concentrations, increased deposition of nitrogen, or changing weather patterns that result from human-induced climate change. Direct effects were generally viewed as management influences that produce a change in greenhouse gas fluxes. However, there was some discussion as to whether a manager also needed to have the intent to influence carbon fluxes to classify the effect as direct. For example, can CO_2 fertilization be considered a direct effect if the decision was made to abandon cropland to forest knowing that CO_2 fertilization would add to the carbon uptake?

BOX 1-3
Direct and Indirect Activities in the Kyoto Protocol

The following description from IPCC (2000b) highlights potential interpretations of direct and indirect activities in the Kyoto Protocol:

The Kyoto Protocol distinguishes between direct and indirect human-induced land use change and forestry activities. The word "direct" precedes the phrase "human-induced" in Article 3.3 but not in Article 3.4. Temporal and spatial immediacy may indicate directness; the closer in time and space the activity is to the impact, the more direct it is. Intent and foreseeability also might be relevant in determining directness.

One of the most significant distinctions between direct activities and indirect influences relates to the effects of CO_2 fertilization and nitrogen deposition. CO_2 fertilization and nitrogen deposition are indirect because the removals are not geographically immediate—that is, they may occur thousands of miles from the site of the emissions. The fact that enhanced growth of biota is a completely unintended consequence of the polluting activity also argues in favor of treating it as an indirect activity. Moreover, CO_2 fertilization and nitrogen deposition cannot reasonably be described as land use change or forestry activities.

Workshop participants also discussed how much of the residual carbon sink can be attributed to indirect effects. Ian Roy Noble commented that there is an assumption that the amount of carbon out of equilibrium can mostly be considered the indirect effect, and both Eric Sundquist and Prather agreed that the residual sink could be considered equal to the indirect effect. However, Richard A. Houghton and Rattan Lal pointed out that current estimates of carbon flux from landuse change are probably incomplete, thus underestimating the current carbon sink attributed to land use change and overestimating the residual sink. For example, a forest's recovery from disturbance 20 years ago may in fact be a past management effect, but it would appear in the carbon budget as part of the residual sink. Houghton noted that if the influence of past management changes on carbon fluxes could be accurately estimated, the indirect effects might appear insignificant. Several workshop participants asserted that current global estimates of the processes contributing to direct effects are too uncertain to determine how much of the current residual sink is determined by indirect effects, while Kimble and Ruth DeFries expressed concern about the large uncertainty associated with the current estimate of the residual carbon sink.

WORKSHOP GOALS

William Hohenstein of the U.S. Department of Agriculture's Global Change Program Office, sponsor of the workshop, emphasized the need for scientific advice to decision makers on the subject of direct and indirect human contributions to terrestrial carbon fluxes. He stated that the role of forests will be a key consideration in greenhouse gas mitigation, given that 30 percent of the current increase in atmospheric CO_2 is attributed to land use and land use change. Policy makers want to understand the role of indirect effects, such as CO_2 fertilization, nitrogen deposition, acidic deposition, temperature and precipitation changes, and tropospheric ozone and whether they have the potential to change the timing or the magnitude of changes in atmospheric carbon concentrations. Hohenstein noted that even though the United States has not signed the Kyoto Protocol, efforts to determine the human influences on land use systems are necessary in the context of reporting CO_2 emissions to the United Nations.

Hohenstein highlighted several issues that motivated the development of the workshop on direct and indirect human contributions to Terrestrial Greenhouse Gas Fluxes. The risks of climate change, such as higher temperatures, changes in precipitation, increased climate variability, and extreme weather events, can result in significant impacts on agricultural and forestry activities; however, agricultural and forestry activities provide an opportunity to mitigate carbon fluxes through targeted land management.

Characterization of these direct and indirect contributions to carbon fluxes will influence decisions on implementation of mitigation and adaptation strategies for agricultural and forestry activities.

Additionally, Hohenstein noted that the need for guidance on direct and indirect effects from land use and land use change activities on national greenhouse gas inventory reporting. Indirect effects of human activities may alter carbon storage on forested and agricultural lands affecting the national greenhouse gas inventory. These indirect human-induced effects on carbon fluxes in forests, for example, could alter the timing of carbon sequestration (i.e., faster growth with trees reaching maturity earlier), the magnitude of carbon sequestration (i.e., increased growth with trees maturing at a larger size), or a combination of both.

Hohenstein specifically presented a number of questions on which policy makers are asking the scientific community for guidance:

- Do indirect human influences affect the timing or magnitude of emissions and removals, or both?
- Can a reasonable "baseline" be established?
- How large are indirect human influences, now and in the future?
- Is it practical to separate direct and indirect human influences?
- How might factoring out indirect human influences change the costs of reporting?
- Can defaults be established? Can rules of thumb be used?
- How should emissions from carbon sequestered by indirect human influences be treated?
- What are the implications for the functioning of the inventory system if indirect human influences are factored out?

Hohenstein commented that advice on these topics was needed in the context of the 10-year strategic plan for the Climate Change Science Program (http://www.climatescience.gov/Library/stratplan2003/default.htm), which focuses not only on understanding the carbon cycle but on decision support and management issues as well.

Therefore, the National Academies convened a workshop on September 23 and 24, 2003, to discuss the current state of scientific understanding on issues related to quantifying the direct human-induced changes in terrestrial carbon stocks and related changes in greenhouse gas emissions and distinguishing these changes from those caused by indirect human effects, natural effects, and past practices on forested or agricultural lands (see Box 1-4).

BOX 1-4
Workshop Goals

The National Academies convened a workshop to discuss the current state of scientific understanding on issues related to quantifying the direct human-induced changes in terrestrial carbon stocks and related changes in greenhouse gas emissions, distinguishing these changes from those caused by indirect human-induced effects, natural effects, and effects due to past practices in forests and current or former agricultural lands. The workshop goals were to examine the following five topics:

1. Methods for quantifying, characterizing, and cross-checking terrestrial carbon stocks over differing timescales and spatial scales.

2. How terrestrial carbon stocks and related greenhouse gas emissions change over time as a function of direct human-induced changes in land use, forestry (afforestation, reforestation, deforestation, and forest management,), and other practices (such as cropland and grazing land management).

3. How terrestrial carbon stocks and related greenhouse gas emissions change over time as a function of indirect human-induced effects (such as CO_2 fertilization, nitrogen deposition, and climate change), natural effects (such as fire frequency and intensity, pests, and climate variability), and past practices in forests and current or former agricultural lands (such as land succession from historical agricultural lands to forests).

4. Methods to distinguish direct human-induced changes in terrestrial carbon stocks and related greenhouse gas emissions from those caused by indirect human-induced effects, natural effects, and effects due to past practices in forests and current or former agricultural lands. Particular attention was to be paid to the following issues:

- the scientific feasibility of partitioning direct human-induced changes from other effects;
- whether it is possible to identify characteristic observations that would distinguish direct human-induced changes from other effects over different spatial scales;
- areas where improved scientific understanding is most needed;
- the costs and technical requirements of applying such methods as part of a national greenhouse gas inventory system; and
- the potential implications for accounting procedures for indirect and natural effects on national and international greenhouse gas inventories, including near-term and longer-term impacts.

5. Efficacy and longevity of varying carbon storage practices and technology.

WORKSHOP SUMMARY

This report summarizes the key technical issues from presentations and discussions that occurred at the workshop. This workshop summary is intended for informed scientists and policy makers as well as interested parties who are well versed on the issue of greenhouse gases, but it covers a range of technical material and thus is not intended as an introduction to the topic of carbon fluxes. This summary is intended to illuminate issues, not resolve them. By its nature, any workshop is necessarily incomplete, and a workshop summary can report only on what was said. With the exception of a few boxes and some cited references that are provided for context and background information, all of the information reported here emerged from presentations and discussions during the workshop. This summary is intended to reflect the variety of opinions expressed by the speakers.

Following this introduction, which describes the context, motivation, and goals for the workshop, Chapter 2 provides a summary of three policy perspectives, focused on national and international activities related to quantifying and reporting direct and indirect human-induced effects on carbon fluxes. Chapter 3 summarizes the science base regarding direct, indirect, and natural effects on carbon fluxes. The workshop speakers provided detailed discussions of the state of knowledge with regard to direct and indirect human-inducted effects, natural effects, and historical land use, reflecting both forestry and agricultural practices. The speakers also presented approaches for partitioning direct from indirect and natural effects. Chapter 3 also summarizes several presentations highlighting data and research needs in this field. Finally, Chapter 4 presents a synopsis of the ideas presented at the workshop, organized according to the five workshop goals presented in Box 1-4.

2

Policy Perspective

Addressing problems of global scale, like climate change, requires coordinated action by people around the world. Although decision makers do not always view problems and solutions the same way scientists do, in many cases they seek scientific input to inform their decisions. This chapter summarizes workshop discussions on the policy context for the science of direct and indirect human contributions to terrestrial carbon fluxes.

TERRESTRIAL ECOSYSTEMS, CARBON STOCKS, AND INTERNATIONAL ACTION

At the workshop, Bob Watson, chief scientist at the World Bank, described terrestrial carbon stocks and the activities of the Intergovernmental Panel on Climate Change (IPCC). He noted that land use, land use change, and forestry (LULUCF) affect both carbon emissions and land-based carbon sinks. The United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol incorporate a set of principles to guide the treatment of LULUCF issues. The UNFCCC principles are intended to exclude carbon removals from CO_2 fertilization, indirect nitrogen deposition, and pre-1990 activities from greenhouse gas accounting. The Kyoto Protocol includes specific text on accounting for changes in carbon stocks related to direct human-induced

BOX 2-1
Carbon Sinks in the Kyoto Protocol

Articles 3.3 and 3.4 of the Kyoto Protocol address issues related to land use, land use change, and forestry in the following excerpts:

> Article 3.3: The net changes in greenhouse gas emissions by sources and removals by sinks resulting from direct human-induced land use change and forestry activities, limited to afforestation, reforestation and deforestation since 1990, measured as verifiable changes in carbon stocks in each commitment period, shall be used to meet the commitments under this Article of each Party included in Annex I.
>
> Article 3.4: The COP [Conference of the Parties] serving as the meeting of the Parties to this Protocol shall, at its first session or as soon as practicable thereafter, decide upon modalities, rules and guidelines as to how, and which, additional human-induced activities related to changes in greenhouse gas emissions by sources and removals by sinks in the agricultural soils and the land use change and forestry categories shall be added to, or subtracted from, the assigned amounts for Parties included in Annex I, taking into account uncertainties, transparency in reporting, verifiability, the methodological work of the IPCC, the advice provided by the SBSTA [Subsidiary Body for Scientific and Technical Advice] in accordance with Article 5 and the decisions of the COP. Such a decision shall apply in the second and subsequent commitment periods. A Party may choose to apply such a decision on these additional human-induced activities for its first commitment period, provided that these activities have taken place since 1990. (UNFCCC, 1997)

LULUCF activities that have occurred since 1990 (see Box 2-1). Article 3.3 addresses afforestation, reforestation,[2] and deforestation and is compulsory for all Annex I countries—the industrialized nations. Article 3.4 covers forest management, cropland management, grazing land management, and human-induced revegetation that has occurred since 1990. Article 3.4 specifies that nations may choose the activities they wish to declare in the first commitment

[2] "Afforestation" is defined as the conversion of land to forest that has not been forested for a period of at least 50 years. "Reforestation" is the conversion to forest of land that has been forested within 50 years but was not forested at the end of 1989.

period,[3] although Annex I countries have a cap at about 100 Megatons (Mt)[4] of carbon per year (equivalent to 0.1 Petagrams (Pg C/yr) of carbon per year) on the amount of forest management credits they can use. Rules for the second commitment period have not yet been set.

Watson noted that, in principle, significant amounts of carbon could be taken up through these various activities. However, an Annex I country can claim no more than 1 percent of its 1990 emissions through LULUCF activities. Moreover, only afforestation and reforestation are eligible in the first commitment period under the Kyoto Protocol's Clean Development Mechanism (CDM).[5] Countries are also not likely to include activities that are costly to measure. Because forest management, logging reduction, and land management are excluded from the CDM, Watson stated, "The types of activities that are probably the most useful for developing countries are probably excluded in the first commitment period." He stated that the potential carbon sink in non-Annex I countries could be 0.4 Pg C/yr (mostly in agroforestry), but that potential has been capped by political agreement to 30 million tons per year across all countries. Watson speculated that if all deforestation were avoided, perhaps 1.6 Pg C/yr could be captured.

Watson noted that accounting for all carbon sinks (direct and indirect) is necessary to ensure the tracking of important carbon fluxes. The proper management of carbon sinks can deliver enormous atmospheric and social benefits; however, the inclusion of carbon sinks in greenhouse gas accounting creates significant and currently unresolved challenges. For example, year-to-year natural global carbon uptake varies by as much as 2 Pg C/yr, and fluctuations from natural causes such as El Niño can be large compared to the yearly commitments specified in the Kyoto Protocol.

The mandate of the IPCC is to assess the natural, technical, and socioeconomic science relevant to anthropogenic climate change. The IPCC LULUCF special report (IPCC, 2000b) concluded that with current scientific tools it may be very difficult, if not impossible, to distinguish that portion of the observed carbon stock change that is directly human induced from that caused by indirect and natural factors. For activities involving land management changes (e.g., tillage to no tillage agriculture), the report concluded that it should be feasible to partially distinguish direct and indirect human induced complements through control plots and modeling but not to separate out natural factors.

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[3] The Kyoto Protocol sets targets that must be achieved as an average over the first commitment period from 2008 until 2012.
[4] Megatons are equivalent to 10^{12}g or 1 teragram.
[5] The Clean Development Mechanism allows Annex I countries to help meet their own emissions targets through sustainable development projects that reduce emissions in non-Annex I countries.

A recent IPCC meeting concluded that there is no practicable methodology for factoring out direct human-induced effects from indirect human-induced and natural effects for any broad range of LULUCF activities (IPCC, 2003). While recognizing that a significant amount of research on CO_2 fertilization is under way, the IPCC noted that paired treatment and control plots do not allow full separation of direct, indirect, and natural effects and provide little information about large landscape effects. The IPCC meeting concluded that many of the effects are nonlinear and nonadditive and that more work is needed to examine synergistic effects and the underlying processes.

Watson suggested three broad approaches for LULUCF that could be applied during the second commitment period or as an alternative to the Kyoto Protocol. First, forest and land management activities in Article 3.4 could be handled on a project-by-project basis, with more manageable monitoring requirements. However, most emissions would not be incorporated at the project level, and Article 3.3 would need to be retained to capture afforestation, reforestation, and deforestation.

As a second approach, Watson proposed comprehensive accounting to include all sources and sinks, although he noted that governments might agree to exclude certain lands (e.g., those with small fluxes that are difficult to monitor). Comprehensive accounting would capture the bulk of greenhouse gas fluxes, but it would also include the current net terrestrial uptake of about 1.4 Pg C/yr, which would occur without any additional effort to reduce emissions or increase sinks (Watson termed this the free ride). Interest in reducing credit for this so-called "free ride" in Annex I countries, he said, was part of the motivation for limiting forest-based credits. Watson commented that there is some debate as to whether the pre-1989 human-induced terrestrial uptake can be factored out with existing scientific capabilities and, if not, whether simple discounting can be fairly applied. He also noted that comprehensive accounting has problems due to the natural variability in carbon fluxes from year to year, but this variability might be addressed by using longer accounting periods, a carbon credit to "banking" system across commitment periods, or continental-scale reporting units to spread out the spatial variability.

Watson presented a third alternative for approaching LULUCF issues, stating that it might be possible to use separate accounts for sinks and nonsink activities and thereby set different targets for emission reductions in the energy/industrial sector and targets for uptake by carbon sinks. An additional issue would need to be addressed as to whether there should be any fungibility between energy sectors and LULUCF.

In summary, Watson stated that sinks are too important to be excluded from greenhouse gas policy. Watson asserted that sinks can be accounted for in an accurate and nondistorting way, addressing issues of permanence of the carbon sink credit based on the land use change enacted. He also commented that the United States is unlikely to reengage in Kyoto (or a successor treaty) without a relatively comprehensive inclusion of sinks. Watson noted some political issues that have hindered the identification of equitable solutions regarding sinks and stated that active cooperation between developed and developing countries will be necessary to effectively address climate change. For example, loss of sovereignty has been a major concern with regard to clean development in non-Annex I countries, although temporary crediting regimes might provide a remedy for these concerns.

GREENHOUSE GAS INVENTORY SYSTEMS

Dina Kruger, chief of the Environmental Protection Agency's Non-CO_2 Gases and Sequestration Branch and a member of the IPCC Task Force Bureau on Greenhouse Gas Inventories, described the national greenhouse gas inventories and emphasized that they must be seen in the context of the UNFCCC and the Kyoto Protocol. She noted that the national inventory serves at least three purposes. First, with its score-keeping function, the inventory is the mechanism by which it is determined whether or not countries are meeting their commitments. As the Kyoto Protocol comes into effect, the national inventory will be the backbone of determining compliance under these targets. Second, the inventory can be used to focus mitigation policies and recognize the major emissions sources and removal sinks. Third, inventories can improve our understanding of global greenhouse gas budgets, helping to determine whether all the sources have been included.

Kruger stated that national greenhouse gas inventories provide average annual point estimates for the six greenhouse gases covered by the UNFCCC and the Kyoto Protocol (CO_2, methane, nitrous oxide, hydrofluorocarbons, perfluorochemicals, and sulfur hexafluoride) The inventories estimate anthropogenic emissions and removals and are completed each year by developed countries and on three- to five-year cycles by developing countries. The inventory is a sizable undertaking, as it covers all sectors of the economy: energy, industry, agriculture land-based and livestock emissions, land change and forestry, and wastes. Developed countries are now preparing annual inventories that cover the time period from 1990 to the present.

The IPCC task force on the national greenhouse gas inventory develops the methods to calculate greenhouse gas emissions and removals (IPCC, 1996, 2000a). There is a range of methods, from very simple (default or "Tier 1" methods) to more data intensive ("Tier 2 or 3"). Because Tier 1 methods are based on global default factors, they will not be as accurate on a regional level, and the two approaches can result in substantive differences. Recognizing that most of the data are collected for other purposes, countries can choose methods based on their more important emissions sources and available data, capacity, and resources, while also following the Good Practice Guidance (IPCC, 2000a).

Kruger explained that in the reporting process the IPCC's role is to identify the types of information that should be included to ensure transparency and facilitate review. The UNFCCC has standardized two-part reporting requirements, which must be submitted annually by Annex I countries. The first part is an extensive set of data tables, including the input data used for the estimates; the second part is the national inventory report, which describes how the estimates were developed and provides documentation and reference material. Under the Kyoto protocol, the parties provide the greenhouse gas inventory, as defined by the UNFCCC, along with supplemental information required for the Kyoto Protocol. For example, supplemental reports may include information on emissions or removals related to Articles 3.3 and 3.4 and activities such as emissions trading, new development mechanisms, and joint submissions.

Consistency across countries is secured through specification of the inventory development process and the types of activities required, along with very extensive reporting guidelines. Each year all the inventories are reviewed by a group of experts. The first step is a quick assessment of the quality of the data, followed by an in-depth review, where teams of 10 to 12 international experts examine the inventory and publish a report considering the following:

- Have appropriate methods been used?
- Are the data appropriate and well documented?
- If a category is particularly important in the inventory, is a higher-tier method used?
- Does the time series date from 1990 forward, and is it internally consistent?
- Are there discontinuities or changes in input data that are not explained or that raise questions?
- What is the system for quality assurance and quality control on the inventory and for assessing the uncertainty?

Data must be sufficient to document the reported achievement of mitigation projects with confidence and credibility.

The Good Practice Guidance (IPCC, 2000a) improved on the 1996 guidelines by including specific direction about quantifying uncertainties in the inventory, so that systematic over- or underestimations can be identified. Because uncertainty depends on both the nature of the sources and the level of effort, there is no prescribed uncertainty threshold. In countries where the bulk of emissions come from energy, such as the United States, good data quality leads to relatively low uncertainty. However, in a country that has a majority of its emissions sources in agriculture, such as Australia or New Zealand, data would express greater interannual variability due to natural fluctuations in the weather and other environmental factors. All developed countries will report quantitative uncertainty of the sources in their inventory and their overall inventory to the UNFCCC.

Kruger concluded by noting that inventories are very resource intensive, both in terms of cost and the number of people involved. In theory, if there were no resource constraints, much more information would be beneficial. However, countries will generally have to prioritize their efforts to achieve an effective balance between scientific completeness and practicality.

In the discussion following Ms. Kruger's presentation, William Hohenstein raised the concern that the five-year greenhouse gas inventory conducted by the U.S. Department of Agriculture is not frequent enough. He noted that more frequent inventory data could provide a better perspective on progress from emissions programs. Eric Sundquist encouraged better use of subnational data to inform the national inventories, which generally exist as single-point estimates. Kruger responded that they are aware of the value of disaggregating the data, although she noted that this level of analysis is partly constrained by available resources.

DEVELOPING THE CAPABILITY TO QUANTIFY SPECIFIC PROCESSES IN THE U.S. CLIMATE CHANGE SCIENCE PROGRAM

Bryan Hannegan, from the Council on Environmental Quality, summarized activities of the U.S. Climate Change Science Program related to carbon budgets and quantifying specific processes. He noted that the Bush administration had just released the strategic plan for the science program, which consists of a near-term climate change research initiative, includes the carbon cycle as one of its major elements, and proposes longer-term fundamental and applied research.

In the near-term initiative, a new $103 million program over the next two years includes clarifying the important processes for carbon fluxes. Hannegan noted that a $10 million National Science Foundation initiative has been proposed for 2005 to focus on understanding the impacts of historical and current trends on a variety of scales. The National Oceanic and Atmospheric Administration will apply resources in areas such as tower- and aircraft- based measurements, vertical profile studies, and maps of CO_2 sources and sinks in the United States President Bush also has asked that an improved accounting system for voluntary emissions reporting be developed. One issue to be resolved will be how to separate indirect and direct effects. Hannegan commented that findings from the near-term work will feed directly into the policy process in a two-to five-year time frame.

Hannegan encouraged scientists to explain the following questions to policy makers:

- What gaps exist in the current understanding of greenhouse gases?
- What measurements and what modeling capacity are required to quantify the North American carbon budget?
- What basic research and what resources are needed in the near term to complete our understanding?
- What specific activities are necessary to answer the policy questions with regard to greenhouse gases?

The administration wants to know the implications for emissions inventories in the context of the voluntary emissions program being pursued. Hannegan said he hoped the workshop could inform policy makers as they grapple with the mechanics of accounting and try to identify specific practices and expected outcomes, so that people are accurately rewarded for sequestering carbon and engaging in practices that will lead to sequestration.

To conclude, Hannegan stressed that policy makers want to be informed by scientists about what is not known or understood and what steps should be taken to fill in these knowledge gaps. Too often, he stated, people advocate what they know, and policy makers are left to determine what information is missing and what research needs to be completed.

3

The Science Base for Direct and Indirect Human Contribution to Carbon Fluxes

Arrhenius first predicted human-induced global warming over 100 years ago based on principles of CO_2 as a greenhouse gas (Arrhenius, 1896). However, it was only after Charles Keeling and colleagues collected several decades of flask data at Mauna Loa showing a consistently increasing atmospheric concentration of CO_2 that climate change began to draw widespread attention (Keeling, 1978; see Figure 1-3). The processes driving climate change and ecosystem response have been, and continue to be, studied rigorously. Considerable work relevant to fluxes of terrestrial greenhouse gases has been done in many fields, and much of this work is pertinent to assessing direct and indirect human contributions. However, scientists are far from having complete knowledge about these complex phenomena, and current research findings may not be sufficiently developed to meet the needs of the decision-making community, because specific research on direct and indirect effects has not been carried out for many of the critical systems around the world. This chapter summarizes the state of the science on direct and indirect human contributions to terrestrial greenhouse gas fluxes, based on presentations made at the September 23-24, 2003, workshop.

DIRECT HUMAN-INDUCED EFFECTS

Estimates of Carbon Stocks and Fluxes from Land Use Changes

Christine Goodale, Cornell University, addressed effects from direct human-induced changes in land use, forestry, and agricultural activities on terrestrial carbon stocks. She described the main land use states, including native vegetation (e.g., forests, grassland, savanna), cropland, pasture, wood harvest and recovery, plantation forests, and others (degradation, restoration, urban/suburban). A host of details affect the estimated carbon sink for each type of land use. For example, in croplands it is necessary to know the types of crops, crop rotation and duration, management regime, and soil amendments. Goodale suggested that sensitivity analyses with existing data and models be used to help discern whether and where such distinctions matter but noted that sufficient data might not currently exist over an adequate time horizon and on relevant spatial scales to make such a determination.

Carbon stocks primarily exist in living biomass, dead biomass, forest floor litter, soil, and wood products. Goodale stated that four key terms affect any estimation of carbon stocks and fluxes: (1) initial carbon stock of the system, (2) immediate or short-term changes in stocks due to land use change, (3) time required for the initial disturbance and for recovery, and (4) the area over which land use change occurs. Initial estimates of carbon stocks are influenced by a number of factors, such as the type, age, and state of an ecosystem. In northern systems this information tends to be relatively well known, but in the Southern Hemisphere the forest carbon stocks are not as well known. For example, Goodale reported that among seven estimates of total forest carbon stocks in the Amazon, the totals ranged from 39 to 93 Pg, and even among those with similar total estimates of carbon stocks, the spatial distribution of biomass varies considerably (Houghton et al., 2001). Knowing the spatial distribution of biomass is important to assess the effect of deforestation in different regions. Goodale suggested that comprehensive inventories of the tropical region and improvements in satellite remote sensing are needed.

Once the initial carbon stock is known, the effect of a particular land use change needs to be determined. Some questions to be answered include what fraction of the initial biomass is killed, how much is removed, how much is burned, and how much is converted into wood products. Inputs and assumptions for all these terms affect estimates of how land use change is altering carbon sinks. Some terms, such as soil carbon loss after cultivation, seem reasonably well constrained, as literature reviews consistently estimate this value at about 25 percent (Mann, 1985; Johnson, 1992; Davidson and Ackerman, 1993; Murty et al., 2002). The effects of forest harvest on soil carbon appear to vary, showing both increases and decreases depending on harvesting method and species type (Johnson and Curtis, 2001), yet harvest impacts are far smaller than cultivation.

The third main factor required to estimate carbon stocks and fluxes is the time necessary for the initial land use disturbance and recovery. The time required for material to decay, for biomass regrowth, for soils to regain biomass, and the expected lifespan of wood products will all affect estimates of the carbon sink.

Goodale asserted that the most important factor for estimating changes in carbon stocks is the area over which the particular land use change is occurring. To highlight this concern, she presented sharply different estimates of surface area deforested based largely on the Food and Agriculture Organization of the United Nations (FAO) statistics (Houghton, 2003) versus estimates from satellite data (Achard et al., 2002; DeFries et al., 2002). Looking at studies worldwide, satellite remote sensing approaches generally show rates of deforestation about 25 percent lower than FAO estimates.

Two main approaches were presented to estimate the source or sink of carbon from land use change across large regions. The first is a model that estimates the net effect of land use change across the past 150 years, both nationally and globally (e.g., Houghton 2003). Goodale termed these "land use bookkeeping models" that do not include natural disturbances, climatic response, or plant physiology. The second approach is through ecosystem process models, which describe the processes and dynamics influencing carbon in plants and soils for terrestrial ecosystems. A more complete summary of ecosystem models presented by George Hurtt can be found later in this chapter.

Richard A. Houghton (2003) estimated that a cumulative total of 150 Pg of carbon has been released globally due to land use change during the past 150 years, and Ruth DeFries et al. (1999) estimated that an additional 60 Pg was released prior to 1850. According to Houghton, the terrestrial carbon flux due to land use change totaled about 2.2 annually during the 1990s. By far the largest source of carbon was the conversion of forest to cropland in tropical regions, followed by deforestation for pastures and logging. However, biogeochemical modeling exercises suggest a smaller source of carbon globally from converted croplands, relative to those calculated by Houghton (e.g., for the 1980s, Houghton estimated 1.2 Pg of carbon, compared to McGuire et al., 2001 who estimated 0.8 Pg). Part of the difference in these estimates may be the initial inputs (e.g., size of disturbance, fraction of regrowth, fraction of loss), but the ecosystem models also show reduced conversion to cropland in the past few decades, whereas the latest bookkeeping models suggest continuous amounts of deforestation and project a net increase in croplands over time.

Goodale summarized this discussion by stating that there is sizable uncertainty in data regarding land use changes and the carbon cycle, in both estimating total area changes and understanding the impacts of key factors on the rates of change. One way that some of these uncertainties can be addressed is through sensitivity analysis, using models and, in some cases, metanalyses of databases. This can help determine where it is most important to include finely detailed land use information and which data are most important.

Estimates of Carbon Stocks and Fluxes from Agricultural Activities

Cesar Izaurralde, Joint Global Change Research Institute,[6] discussed the effects of agricultural activities on the magnitude and fluxes of soil carbon pools. He noted that there is the potential for increasing carbon storage through improved management of cropland, rice paddies, agroforestry, and grazing land both in Annex I and non-Annex I countries (see Table 3-1). Management choices that may be considered for croplands include reduced tillage, crop rotation, cover crops, fertility management, erosion control, and irrigation management. Improved management of irrigation, plant residue, and fertilizers can be considered for rice paddies, while tree and cropland management offer potential for agroforestry. Izaurralde commented that while the impacts of individual management approaches are known for a particular soil, the interactions among multiple techniques and across multiple scales are currently not as well understood.

There currently are about 70 million hectares (ha) of land in the world under no tillage or direct seeding—a fairly recent conversion. In the United States, the use of no tillage agriculture has increased consistently over the past 12 years (CTIC, 2002), which may in part be due to the introduction of herbicide-resistant crops. Izaurralde noted that the potential effects of wider conversion to no tillage on both carbon and erosion needs to be better understood. Rough calculations based on the results of West and Post (2002) suggest that current no tillage agriculture is sequestering 0.04 Pg C/yr globally, although the IPCC (1996) estimates a potential sequestration of 0.7 ± 0.2 Pg C/yr with a range of agricultural activities.

Work by Ogle et al. (2003) was presented as an example of the degree of uncertainty in the estimations of land use change and management effects on soil organic carbon stocks. Ogle and colleagues used an inventory-type estimation of soil carbon change in the United States between 1982 and 1997 and developed density functions for soil carbon stocks, land use conditions, and management factors. They then used Monte Carlo simulations to approximate carbon sources or sinks for mineral soils and organic soils. Ultimately, they concluded that for all soils there was a net sink of 1.3 ± 5.6 teragrams of carbon per year (Tg C/yr or 10^{12}g C/yr), with the high

[6] A collaboration of the Pacific Northwest National Laboratory and the University of Maryland.

uncertainty attributed to soil type, age factors, and land use change. Nevertheless, Ogle et al. concluded that there is a large potential for carbon sequestration in U.S. agricultural soils.

Izaurralde presented examples of studies that conducted detailed field sampling of soil organic matter across large areas in Argentina and Saskatchewan, Canada, after conversion to no tillage management. In the Argentinean study, Casas (2003) found that soil organic matter in the top 5 centimeters increased after producers used no tillage practices for 8 to 11 years. McConkey et al. (2000) reported an average soil increase of 1.46 megagrams of carbon per hectare (Mg C/ha or 10^6 C/ha) after three years of no tillage practice in 138 fields across Saskatchewan.

Izaurralde noted that soil inorganic carbon represents 38 percent of the total soil carbon pool (Wilding et al., 2002), yet much less is known about what happens with inorganic carbon based on agricultural practices. Land use may affect inorganic carbon pools through irrigation management, fertilization practices, land tilling and cropping, and erosion effects.

In closing, Izaurralde stressed that carbon sequestration modeling requires increased efforts to characterize agricultural activities at global scales under specific environmental conditions. Current uncertainties can be reduced through a network of field-scale studies, the development of protocols for monitoring and remote sensing, and the use of ecosystem models to scale sequestration rates over large regions.

In the discussion following Izaurralde's presentation, an audience member raised the point that conversion to no tillage agriculture minimizes soil erosion, thereby further reducing carbon losses. Izaurralde agreed that this added effect of no tillage is likely significant but that currently there is uncertainty about the impact of eroded sediments on the carbon cycle. Kimble added that more farmers would convert to no tillage practices were it not for the temporary drop in yield that occurs for two to three years after the management change. Schlesinger also expressed concern that the carbon costs of agricultural management be considered, such as the carbon costs of fertilizer production or irrigation. According to Rattan Lal, producing 1 kilogram of nitrogen fertilizer requires 1 kg of carbon, while 1 kg of phosphorus production requires 4.3 kg of carbon. However, Lal noted the potential beneficial aspects of incorporating increased carbon sequestration into ongoing food production through improved management. Considering the additional carbon inputs that occur through the intensification of land management, Schlesinger expressed skepticism that agricultural management approaches could result in a sizable net sink—at least one that could offset carbon emissions.

TABLE 3-1 Potential Area and Carbon Storage for Activities under Article 3.4. of the Kyoto Protocol

	Annex I		Non-Annex I	
	Area (10^6 ha)	2010 C rate (Tg C y-1)	Area (10^6 ha)	2010 C rate (Tg C y-1)
Improved Management				
Cropland	589	75	700	50
Rice paddies	4	1	149	7
Agroforestry	83	12	317	14
Grazing land	1,297	69	2,104	168
Land Use Change				
Land restoration	12	1	265	3
Grassland	602	24	855	14

Source: Sampson and Scoles (2000).

Effects of Land Succession from Historical Agricultural Lands to Forests and Historical Practices in Forests

Chris Potter, National Aeronautics and Space Administration Ames Research Center, discussed historical practices in forests and successional processes when agricultural lands are allowed to become reforested. He noted that the most relevant successional processes from agriculture to forest are abandonment followed by natural woody regrowth and abandonment followed by active afforestation. Three important historical practices are selective harvest, clear-cut, and managed burn. These processes and practices affect carbon pools in above-ground biomass, below-ground biomass, forest floor woody biomass, and soil organic matter.

The most common way to define successional or historical state is by the number of years since agricultural abandonment or since the last major disturbance. Potter noted that a number of sources suggest historical declines of croplands between 5 and 10 percent over the past 50 years in the United States (National Resources Inventory [USDA], Economic Research Service, and the Census of Agriculture). These croplands have generally not been actively afforested but have been allowed to lie idle. The extent to which differences in successional state and history need to be resolved to capture carbon fluxes, Potter said, depends on the ecosystem carbon pool of interest, the types of previous agricultural use, and the number and type of plant species at each stage of succession.

Potter presented research results related to the four carbon pools to describe the magnitudes and uncertainties in carbon stocks and fluxes from different successional states and historical practices. With respect to above-ground forest carbon, Potter noted that rangeland in the West is gradually undergoing regrowth due to fire suppression and woody species invasion, leading to a large increase in above-ground carbon storage (Archer, 1995). A comparison of active reforestation to natural hardwood succession in Maine between 1982 and 1995, for example, shows increased carbon in above-ground biomass for active conifer reforestation (Griffith and Alerich, 1996). Potter noted that selective cutting with fire management can produce the same amount of forest products as clear cutting while increasing above-ground forest carbon storage (Harmon and Marks, 2002). Tree species composition can also significantly influence the amount of carbon stored in above-ground biomass (Schuster et al., in press). With respect to below-ground carbon storage, Potter presented research showing that carbon allocation to live roots in mature forests is roughly twice that of above-ground litterfall, although this likely declines with forest age (Davidson et al., 2002).

Dead wood biomass accumulates relatively rapidly during the first 20 years of forest development, but then it slows down considerably between 30 and 80 years (Smith and Heath, 2002). Potter also noted that the amount of carbon storage in dead wood was greater in a pine plantation versus a naturally regenerated oak forest (Currie and Nadelhoffer, 2002).

Potter then described the effects of afforestation on the soil organic carbon pool with stand age and historical practices. Research has shown that soil organic carbon increases with afforestation that follows cropland uses but decreases for afforestation following pasture land uses (Polglase et al., 2000). A comparison among old-growth, second-growth, and young-growth forests in the West shows a notable increase in the soil carbon with forest age in both the soil organic layer and the top 10 centimeters of mineral soil (Entry and Emminghan, 1998). Potter commented that the mineral soil layer is probably the most recalcitrant, long-term carbon pool.

In order to reduce uncertainties related to land succession, Potter suggested high-resolution remote sensing to classify and map disturbance types, ages, and land cover changes and satellite lidar products to classify and map forest height and age. He also identified a need for full ecosystem modeling, which starts from the disturbance and includes successional processes, with model validation in representative forest types across the country.

Potter closed by describing the model CASA (http://geo.arc.nasa.gov/sge/casa/), which presents data for carbon pools and fluxes for the continental United States at a resolution of 8 kilometers. Potter described other recent data analysis advances that are reconstructing disturbances from a 20-year dataset of greenness patterns around the world at an 8-kilometer resolution.

Efficacy and Longevity of Varying Carbon Storage Practices

Tristram West, Oak Ridge National Laboratory, addressed two issues: the implications of considering direct human-induced and other effects on the efficacy of varying carbon storage practices and how human-induced and other effects change the longevity of varying carbon storage practices.

With regard to the comparison of human-induced and natural changes, West noted that the majority of the natural variation and sampling error can be canceled out using baseline data. For example, by comparing soil carbon storage under the use of manure versus synthetic fertilizer, he noted that the difference between the two treatments represents the change associated with the management practice and effectively cancels out natural variation. Using such comparative treatments, Buyanovsky and Wagner (1998) showed that the increase in soil organic carbon for manure-treated fields started to saturate after 50 to 60 years. Baselines also can be used to estimate avoidance of carbon loss through agricultural practices, as illustrated in a comparison between synthetic and organic fertilizers by Uhlen (1991).

West stated that the efficacy and longevity of carbon storage practices depend greatly on previous land use history. Basically, the more carbon loss due to previous land management, the greater the potential to store carbon in the future. However, after a certain amount of time soil carbon may reach a saturation point. Efficacy and longevity of carbon storage practices also depend on mean annual temperature, precipitation, and percent radiation. For example, West presented data from several experiments, which potentially show an increase in soil carbon associated with a climate anomaly in the early 1990s (West, 2003).

Although the change from conventional tillage to no till decreases losses in soil carbon, this effect levels off after a couple decades (West et al., 2003). However, West noted that carbon savings associated with decreased emissions will continue indefinitely, as long as the no tillage management practice continues (West and Marland, 2002). Similarly, conversion from cropland to grassland can reduce net carbon flux to the atmosphere due to reduced inputs, more than soil carbon storage alone (West, 2003). Meanwhile, these carbon storage practices affect other greenhouse gases. Carbon sequestered in soil as a result of manure application may be offset by methane emissions, for example, if the manure management uses liquid/slurry rather than solid manure (West, 2003). West commented that other resources (e.g., fossil fuels, energy) may be impacted from the carbon storage practice, further affecting net emissions (Schlamadinger and Marland, 1996).

West then addressed human-induced and other effects on the longevity of carbon storage practices. Different land management practices affect the rate of carbon accumulation or loss, the duration of those rates prior to a new steady state, and the efficacy of the carbon storage practice. Although carbon stocks may reach a new steady state, changes in emissions will persist as long as the new management continues.

West then proposed using carbon management response (CMR) curves to address issues of efficacy and longevity. The CMR curves represent the global mean change in carbon fluxes from soil (with 95 percent confidence intervals) following a specific change in management practice. These curves are based on paired data and therefore eliminate much of the natural variation (West et al., 2003). Several management effects can be combined in a single series to determine the impact of multiple management changes from baseline conditions.

In summary, West said that carbon storage practices affect the latent duration of carbon accumulation and loss and that direct human-induced versus natural or indirect changes in carbon stocks can largely be resolved using baselines. The efficacy and longevity of carbon storage practices depend greatly on previous land use history and are therefore dependent on each project or land area. Accounting methods, such as CMR curves, can be defined to consider direct human-induced changes in carbon stocks and net greenhouse gas emissions resulting from carbon storage practices. In practice, such a system could be scaled up to estimate direct human-induced effects for the purpose of national inventories by applying information for specific soil or climate classes across the entire country.

West concluded by posing several research needs, including analysis of paired data over extended time periods with short iterative sample periods and standard protocols for measurement observations. West also suggested full greenhouse gas accounting for proposed carbon storage practices, monitoring and analysis of socioeconomic impacts from carbon storage practices, a better understanding of the interactive effects of management practices on carbon stocks and greenhouse gas emissions, and a compilation of existing datasets.

In the discussion period, West and Kimble expressed confidence that agricultural management effects could be separated out through the use of control plots and small field experiments, and West noted that these experiments could be used to calculate large regional estimates. Nevertheless, some participants expressed concern about the ability to scale these results so that they are applicable to a national inventory. Hamilton said that scientists can give policy makers a “top-down” estimate of indirect effects but cannot calculate the same figure from the bottom up by scaling plot-level data. Kimble and Brown added that it would be prohibitively expensive to design and conduct the controlled experiments for a precise bottom-up approach.

INDIRECT HUMAN-INDUCED AND NATURAL EFFECTS

Nitrogen Deposition, Carbon Dioxide, and Climate Change

Dennis Ojima, Colorado State University, discussed the influence of indirect human-induced effects from CO_2, nitrogen, and climate on carbon sequestration processes as well as direct effects from nitrogen use in agriculture. Over the past 30 years, there has been a marked increase in the amount of synthetic fertilizer produced and the acreage of soybean crops and other nitrogen-fixing legumes. Ojima noted that anthropogenic nitrogen inputs now equal or surpass estimates of natural nitrogen fixation. He stressed that nitrogen is important to include when considering the direct and indirect influences on greenhouse gas emissions. In terms of the nitrous oxide budget, land processes (e.g., forest, agricultural soils, feedlots) have a very large impact on the net release of nitrous oxide into the atmosphere, and nitrogen increasingly affects the ammonium cycle, especially through livestock production (Galloway and Cowling, 2002). Ojima presented data that showed increasing nitrous oxide emissions over 75 years of high-intensity agriculture but declining carbon sequestration in soil organic matter, leading to a gradual increase in net greenhouse gas emissions. He noted that nitrogen could be better managed to optimize the soil organic matter accumulation.

Ojima noted that global depositions of nitrogen appear to have large impacts on the net ecosystem production (NEP) of carbon.[7] Townsend et al. (1996) showed that the spatial distribution of the carbon sink can be attributed to nitrogen deposition worldwide. These results reveal the total global carbon uptake from fossil fuel nitrogen deposition to be 0.74 Pg/yr, although the number is reduced to 0.4 Pg/yr when nitrogen losses are taken into account.

Influences on the terrestrial carbon balance have widely variable timescales. Key aspects of carbon exchange respond quite rapidly to environmental changes, such as changes in soil moisture and temperature. Other factors range in timescale (e.g., a week for leaf nitrogen, seasons for microbial respiration of leaf litter, years to centuries for respiration of soil carbon). Infestations and fires have episodic and sometimes seasonal dynamics that influence the net ecosystem exchange in terms of disturbance. This combination of fast and slower responses can lead to annual variability in carbon exchange. Presenting model simulations based on the Harvard Forest

[7] Gross primary production (GPP) is the amount of energy trapped in organic matter at a given trophic level, equal to the net primary production (NPP) plus the amount lost to respiration by plants and other autotrophic organisms. NEP equals NPP minus the amount lost to respiration by decomposers and other heterotrophic organisms, such as grazers.

and Finland, Ojima noted that climate perturbations and other disturbances influence the expansion of leaves, relative seniority, or changes in litter inputs into the system, which in turn influence nitrogen feedbacks (Ojima, 2003). These disturbances can have long-term nonlinear effects because of the different timescales of the processes involved.

Ojima discussed the effect of CO_2 enrichment and noted that researchers have observed variable changes under conditions of chamber-enriched CO_2 according to the species examined (Morgan et al., 2004). Others have found that climate has a big impact on the expression of a CO_2 fertilization effect (e.g., Owensby et al., 1999), as the effects of elevated CO_2 chamber experiments on productivity have been much higher in dry years. Additional research on CO_2 fertilization was described at the workshop by DeLucia and is summarized in the next section.

Interactions are important to the net ecosystem exchange because process interactions are not simply additive. For example, nitrogen and CO_2 show increases in net ecosystem exchange (NEE) due to their interactions (Thornton et al., 2002), and precipitation affects the interaction between nitrogen and CO_2 (Ojima, 2003). These indirect factors interact with each other differently depending on the plant community and are influenced by species-level changes.

To summarize, management of crops and nitrogen is important when considering rates of carbon sequestration and greenhouse gas emissions. Coupled biogeochemical interactions affect system-level responses to the various perturbations of climate, CO_2, and nitrogen. Animal effects, including livestock, can also modify sequestration potential.

Effects of Carbon Dioxide Enrichment and Climate on Forestry Productivity

Evan DeLucia, University of Illinois, discussed CO_2 enrichment and climate effects on forest productivity and their relevance to global carbon cycles. He asserted that forestry activities are a dominant player in the global carbon cycle because there are large carbon storage pools in terrestrial ecosystems, with the vast majority being stored in trees.

While there are good, reliable equations for predicting GPP, the respiratory components are the major uncertainties in the physiological responses of forest carbon stocks. DeLucia asserted that these respiratory fluxes drive the interannual variation in global productivity, yet our understanding of scaling these fluxes remains at a rudimentary level. Even though soil carbon represents a more recalcitrant carbon pool, from a carbon stock perspective it is more effective to manage forests for NPP and biomass accumulation, since soil carbon pools are built over hundreds of years at rates that are one to two orders of magnitude slower than net primary production. He also noted that recalcitrant soil carbon pools can become filled over time.

DeLucia then described the Forest-Atmosphere Carbon Transfer and Storage (FACTS-1) experiment at Duke Forest in North Carolina examining the extent of forest growth and respiration on stimulation with 570 parts per million CO_2 (see Figure 3-1). This concentration is approximately what is expected to occur in 2050, and the experimental plots are compared to several control plots at ambient CO_2 concentrations of 370 ppm. Duke Forest is a pine plantation that had been unmanaged since planting 18 years before the start of the experiment in 1996.

DeLucia reported that every year there has been a substantial stimulation in the elevated CO_2 plots compared to the control plots—from 15 to above 20 percent. Over the first seven years of this experiment, despite growing on fairly nitrogen- and phosphorus-deficient soil, a sustained growth response in relative basal area increment to elevated CO_2 has been observed. Schlesinger, however, presented other data from the FACTS-1 experiment showing a declining growth response in tree ring growth over time. In the early years of the experiment as much as 25 percent increased tree ring growth with CO_2 enhancement was observed, compared to an 8 to 10 percent increase today (Schlesinger, 2003). DeLucia speculated that nitrogen may become a limitation because the current rates of nitrogen utilization exceed those of nitrogen mineralization. He also noted that under CO_2 enrichment, trees of a given size are reproducing earlier and cone production is greater.

A carbon budget was generated for this forest with and without CO_2 enrichment for the year 1999 (see Figure 3-2). The sizable stimulation in GPP is not accompanied by a detectable difference in plant respiration in response to elevated CO_2. There is, however, a significant stimulation in heterotrophic respiration (R_h) mostly caused by increased litter inputs to the soil and greater microbial activity. Litterfall contributes substantially to the total NPP, which increased 27 to 30 percent under elevated CO_2 conditions. Even with the increase in heterotrophic respiration, there is a 41 percent increase in NEP in this forest with CO_2 enrichment. DeLucia noted that a 41 percent increase in NEP in the year 2050, assuming current land use patterns and current distribution of forests, would offset about 10 percent of the expected fossil fuel emissions. Schlesinger asserted, “The sink is not going to be enough to satisfy all the policy makers’ needs if we take global warming seriously.”

The magnitude of the CO_2 stimulation shows notable heterogeneity over time (DeLucia, 2003). While precipitation increases NPP, it does not explain the magnitude of the CO_2 fertilization. DeLucia and colleagues found that the difference in the observed extent of CO_2 stimulation is explained solely by temperature. In warm years the stimulation caused by elevated CO_2 is greater than in cold years. There is large interannual variation in NPP, much of which DeLucia said is explained by respiration. Much of that interannual variation in respiratory fluxes seems to correspond with El Niño and La Niña cycles, although the regulation of respiration processes remains poorly understood. In a subsequent discussion, Schlesinger pointed out that other drivers, including ozone or drought, may be causing the observed interannual variation in CO_2 stimulation.

In summary, DeLucia stated that atmospheric CO_2 is tightly coupled with forest production and that photosynthesis will be stimulated in any ecosystem where CO_2 is elevated. Because of large uncertainties in respiration, how CO_2 enrichment translates into NEP and NPP remains poorly understood.

FIGURE 3-1 The FACTS-1 experiment in the Duke Forest in North Carolina. Source: DeLucia (2003)

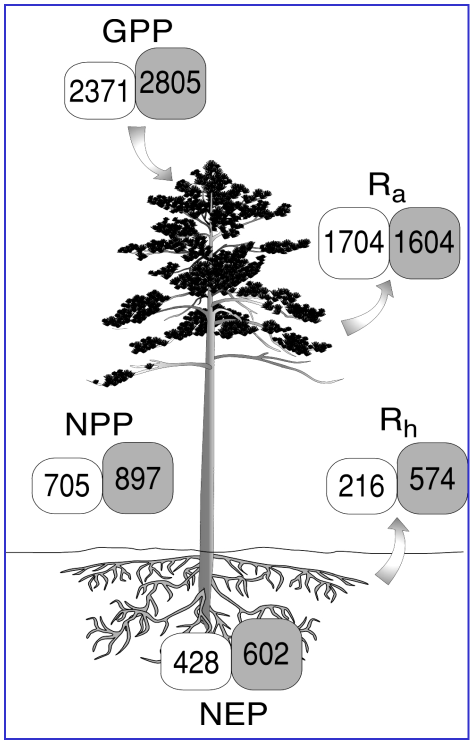

FIGURE 3-2 Carbon budget for a pine forest under CO_2 enrichment in the FACTS-1 experiment. Open bubbles represent ambient plots; closed bubbles represent elevated atmospheric CO_2 plots. Units are expressed in grams of carbon per meter^2 per year. GPP represents annual photosynthesis; respiration from plants (R_a) and soil microbes (R_h) return large quantities of carbon to the atmosphere; NPP represents the annual increment of carbon in the ecosystem and NEP represents the accumulation of carbon following losses by R_h.
Source: DeLucia et al. (2003)

Natural Effects on Forest Carbon Dynamics: Demography, Growth, and Fire

Nathan Stephenson, U.S. Geological Survey (USGS), provided an overview of natural effects on forest carbon dynamics. He emphasized the topics of demography, forest death and growth rates, and fire and their influences on carbon stocks.

First, he said that demography is potentially more important than growth rate in determining carbon dynamics. The mass of individual trees differs by age and even though most of the individuals are in the young-age classes, the bulk of forest carbon lies in middle-age classes. In order to increase carbon storage in a forest, one might reasonably expect a greater response by decreasing the death rate than by increasing the growth rate. Whereas a 10 percent increase in growth at a constant death rate results in a 10 percent increase in equilibrium forest stand mass, if the growth rate remains constant and the death rate decreases by 10 percent, one might expect a 50 percent increase in stand biomass.

Stephenson noted, however, that the death rate and growth rate are closely related and that the relationship between these factors can be affected by such influences as climate or pests. Stephenson presented results from annual resolution data for about 20,000 individual trees in the Sierra Nevada, which showed a possible macroclimatic effect on tree death rates, since the death rate decreased with elevation (Stephenson, 2003).

He noted that the relationship between tree growth and death varies among causes of death, which has implications for carbon dynamics. Stephenson defined three broad classes of tree death: mechanical mortality (breaking or uprooting), biotic mortality (mostly insects and pathogens), and stress mortality. However, he noted that gap models of forest dynamics have only two categories of tree death: ambient mortality (independent of growth rate) and vigor mortality (where slow growth correlates with higher mortality). In contrast to the assumptions of the gap models, based on his own data analysis from the Sierra Nevada plots, Stephenson did not find a cause of death that was independent of growth rate, and each of the three tree death classes showed a different correlation with growth rate (Stephenson, 2003). He suggested that if storm frequency and intensity increase with climate change, mechanical mortality may increase substantially as it is least dependent on growth rate.

Stephenson expressed concern with another model assumption from gap models of forest dynamics, by noting that annual net carbon gain by trees does not necessarily reach a plateau. He presented data from Clark and Clark (1999), which showed that for many tropical tree species studied, at least among rapidly growing trees, it is possible for the trees to continually increase the amount of carbon they add each year as they get larger. Stephenson also noted data from giant sequoias (Stephenson, 2003) where the annual diameter growth rate (or ring width) remained relatively constant despite an increasing diameter, suggesting a huge increase in carbon uptake into wood mass over time.

Stephenson then described the impact of forest fire suppression on carbon fluxes. He noted that fire suppression can make some forests less stable and less resilient to fire, such that a severe wildfire could cause a sudden and large injection of carbon into the atmosphere. When a forest is stable and resilient to fire, surface fires are not likely to change the forest structure. He presented data on a specific intense prescribed fire for a plot dominated by white firs, and noted that the live bole mass of the plot decreased by about one-third within approximately 10 years after the prescribed fire (Stephenson, 2003). As a result of the prescribed burn, the forest plot enhanced its resistance and resilience to a catastrophic fire, in exchange for the loss of some carbon. He noted that the national Fire and Fire Surrogate study (http://www.fs.fed.us/ffs/) would be an excellent opportunity to examine the effects of forest management (thinning and prescribed burns) on forest carbon sequestration at the biome level.

Stephenson asserted that a network of forest gauging stations, checked annually, is needed to understand the causes of tree mortality and measure growth and reproduction for living trees. He proposed that such a rigorous data collection network would be needed to help track the mechanisms driving changes in carbon stocks. Stephenson asserted that the current knowledge of the mechanisms driving forest carbon dynamics is too weak to reach any meaningful conclusions about partitioning out direct, indirect, and natural contributions.

PARTITIONING INDIRECT AND NATURAL EFFECTS FROM DIRECT HUMAN-INDUCED EFFECTS

Separating Direct Human-Induced Changes from Other Effects

Richard Birdsey, USDA Forest Service, presented work by Jennifer Jenkins, of the University of Vermont, on partitioning direct human-induced changes from other effects. The Intergovernmental Panel on Climate Change Special Report on Land Use, Land use Change, and Forestry (IPCC, 2000b) reports the effects of various land use transitions on different carbon pools. Birdsey presented global estimates of the direct human-induced effects (based on the IPCC definitional scenario) pertinent to Article 3.3 of the Kyoto Protocol. For the time period 2008 to 2012, afforestation and reforestation activities are expected to cause a sink totaling between 0.197 and 0.584 Pg C/yr worldwide. Deforestation is estimated to be 1.788 Pg C/yr, yielding a net source of approximately 1.2 to 1.6 Pg C/yr (IPCC, 2000b).

The IPCC has defined many different kinds of practices that could be included under Article 3.4 of the Kyoto Protocol, if countries elect to do so (see Chapter 2 for a further discussion of Articles 3.3 and 3.4). Birdsey presented recent estimates of direct human-induced effects pertinent to Article

3.4 activities, which estimate a potential net change of about 300 megatons[8] of carbon per year (or 0.3 Pg C/yr) for Annex I countries for the year 2010. The global potential net change in carbon stocks due to land use management and land use change (reflecting all countries) is estimated at approximately 1 Pg C/yr for the same time period (IPCC, 2000b).

If it can be assumed that the change in carbon (ΔC) is equal to the three effects - natural, indirect human-induced effects, and direct human-induced effects - direct effects could be calculated by:

Direct human-induced effects = ΔC - natural effects minus indirect human-induced effects.

For inventory reporting, at least from a policy viewpoint, it may not be necessary to sort out every other effect individually. However, Jenkins questioned whether there is enough information about direct human-induced effects or the sum of natural plus indirect human induced effects to calculate the direct human induced effects with confidence. Birdsey noted that much more detail about the processes operating on these systems may be needed to estimate direct human-induced effects.

Jenkins suggested several approaches for estimating direct human-induced effects, such as using controlled plot experiments to compare the effects of various management strategies at small spatial scales. For scaling up to larger areas, one approach would be to use data from small-scale research plots to infer characteristics of larger landscapes that have similar characteristics. A second approach is to adapt existing inventory systems to sample the components of direct human-induced effects, by estimating the area of the activity that is taking place (e.g., forest fertilization) and the change in carbon per unit area. A third approach for estimating direct effects is through model-based inquiries, which can integrate the results from small-scale research studies, inventory systems, and remote sensing, as discussed by Hurtt.

In summary, Jenkins identified several categories of research and data needs to improve confidence in current understanding of direct human-induced effects and their magnitudes. These research areas include forest management, grassland management, wetlands management, and conversion to agroforestry. Specifically focusing on afforestation, reforestation, and deforestation research needs, Jenkins suggested that future research focus on land use and cultivation history, species composition, site and soil characteristics, and the temporal scale of ecosystem response in order to reduce uncertainty about the magnitude of the effects. Jenkins also highlighted the attribution of current carbon sinks as a major uncertainty in current

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[8] Megatons are equivalent to 10^{12}g or 1 teragram.

understanding. Birdsey noted that forests are changed for long periods after disturbance events; thus, additional research on the effects of past practices would be an important contribution.

In the discussion following Birdsey's presentation, several workshop participants, including John Kimble, expressed concern that indirect and direct effects cannot be quantitatively separated out. Birdsey noted that the difficulty in partitioning direct and indirect effects comes in part from the current limitations in measuring effects. Additional workshop discussions on separating direct and indirect effects are summarized in Chapter 4.

Implications for Indirect and Natural Effects on National and International Greenhouse Gas Inventories

Christopher Field, of the Carnegie Institution, addressed indirect and natural effects for national and international greenhouse gas inventories. He noted that the entire terrestrial sink is the result of indirect effects and past practices, little of which occurred after 1990 due to purposeful management. Thus, he stated that no credit should be attached to the current sink, saying that "the factoring-out problem is really a problem for the future . . . not a legacy of the past."

West noted that factoring out direct and indirect effects is the right thing to do strategically, ethically, and economically. However, even with a good program to factor out indirect effects from direct ones, the possibility of inequities exists. For example, carbon sinks from purposeful management actions in one place might result in carbon sources elsewhere (also called "leakage"). Other inequities can occur when the separation of indirect and direct effects is estimated incorrectly.

There are, however, intrinsic problems with factoring out direct and indirect effects at the project level. Field stated that factoring out is much less problematic in the context of full carbon accounting than focused carbon accounting. According to the IPCC (2000b), "the term 'full carbon accounting' can be used to imply complete accounting for changes in carbon stocks across all carbon pools, landscape units, and time periods" and includes both natural or human-induced effects on carbon stocks. The Kyoto Protocol uses a focused accounting approach, which "mandates that accounting be restricted to certain 'human-induced' activities". Factoring out direct and indirect effects focuses on some processes at particular sites, whereas full carbon accounting addresses all processes in a spatially comprehensive manner. For example, factoring out is susceptible to leakage, but full carbon accounting would address this and also be more amenable to top-down constraints. In addition, other greenhouse gases associated with carbon sequestration or carbon management could be included in a full carbon accounting. However, both methods have difficulty accounting for random effects, such as pest outbreaks and storms.

The underlying assumption of factoring out is that a quantity can be assigned to carbon storage at the landscape scale, which is a result of direct human actions, even though there are random factors that impact the landscape on a regular basis. Field asserted that "precisely separating random from management impacts will not be possible, over economically and ecologically meaningful domains of space and time." He noted that this separation will be most difficult at the landscape scale and suggested the need to incorporate a probabilistic component into the assignment of carbon credits. Field also noted that the Marrakesh Accords (UNFCCC, 2001) have been interpreted to suggest that the accounting of management effects should be made in the absence of all indirect effects, which requires either complicated manipulative experiments replicating an earlier pristine state or complex process models.

Field then described the limited relevance of past carbon cycle research to the problem of assigning credit for carbon management. He presented a sample project to separate indirect effects from direct effects for ammonia fertilization in a forest, assessing carbon gains that are corrected for indirect effects at the landscape scale and losses due to harvesting, disturbance, and leakage. He then described five approaches to the accounting process:

- *Standard values* from the literature combine experimental results and informal syntheses that should represent the community's consensus about how these processes work. Of course, there would be limited accuracy and ability to deal with regional subtlety, and there would be some management systems that are more compatible with standard values than others.
- *Multifactor manipulations* provide at least the possibility of directly testing a management scheme over many decades. Forest fumigation experiments, for example, provide the opportunity to analyze a management effect with the indirect effect of elevated CO_2. However, there are timescale issues and difficulties when assessing the implications of past effects in multifactor manipulation.
- *Control plot approaches* are probably the most compatible with available technology. In this case, reference plots can be set aside to determine the effects of management where both treatments are influenced by indirect effects (similar to West's concept of baseline data presented previously). This approach is transparent and practicable, although it is much more complicated on a regional scale. It is also difficult to establish a control on insect outbreaks, fires, and other random events. However, control plots will become

increasingly irrelevant if negotiators insist on knowing management effects in the absence of indirect influences.

- Bottom-up models (process-based models) address a wide range of mechanisms and interactions that could, in principle, be validated. However, Field remarked that there are not yet models for all the relevant processes, and they are not accurate at all the relevant scales. Nevertheless, bottom-up models can indicate important constraints over the long term.
- Top-down models (based on inverse modeling and aggregate data), in principle, could be used with a spatial map of the carbon sequestration or loss attributable to each of the major mechanisms, such as fire or tropical regrowth. An atmospheric inversion could be used to calculate the carbon exchange in each mechanism. Field's own research, however, suggests that the results were strongly influenced by initial estimates.

Field concluded by stating that factoring out direct and indirect effects could be advanced using a progression of approaches. With a serious investment, Field asserted, fixed values can be developed that are relevant and appropriate for a large fraction of the proposed carbon management projects. In many cases, those fixed values could be constrained immediately with appropriate control plots. Over a decade or so, the constraints from control plots could be improved with additional information from manipulative experiments and bottom-up models, and in the long term, bottom-up and top-down models ought to provide precise, flexible constraints.

Research Needed to Enable Partitioning of Direct and Indirect Effects

Jim Randerson, University of California at Irvine, discussed the research needed to enable partitioning of direct and indirect carbon sinks. Randerson briefly summarized key uncertainties from previous discussions. In terms of direct effects including land use change, he said that there remains high uncertainty in delineating cleared, disturbed, and managed areas and in understanding the consequences of different management strategies and the trajectories of carbon stocks following management transitions. With regard to indirect effects, he noted that photosynthetic responses are relatively well characterized, but there is uncertainty regarding allocation, respiration, and fire responses, especially on decadal timescales.

In this context, Randerson identified key components of a research program that he thought would yield the greatest return in terms of reducing uncertainties associated with the carbon cycle and understanding direct human impacts better. Current uncertainties in the trace gas inventories, he said, greatly limit the application of atmospheric observations for determining regional distributions of sources and sinks. Randerson stated that greater temporal and spatial detail in trace gas inventories would enable linkages to near-real-time emissions, energy use levels, and climate data. One approach to prioritizing trace gas research needs would be to conduct a cost-benefit analysis on the research for reducing uncertainty with respect to each trace gas. Randerson also stated that independent approaches should be fostered to expand on the few existing data threads. He suggested that a center jointly sponsored by multiple agencies could promote synergism between different aspects of trace gas inventory work.

Randerson described research goals for biospheric sources and sinks, including more detailed inventories, improved synthesis of carbon trajectories following disturbance or management transitions for different biomes and agricultural systems, and a new research approach for understanding the consequences of different management strategies. He proposed a new program for experimental manipulation of management regimes, analogous to Long Term Ecological Research sites. Such a program could pull together and standardize many different datasets and conduct controlled experiments. Randerson also identified the need for more research using top-down constraints and examining nonlinear interactions.

In summary, Randerson presented the following three steps that should move forward as soon as possible: (1) a cost-benefit analysis on the science and financial investment required to reduce trace gas uncertainties, (2) an annual mapping of large-scale disturbance events globally, and (3) reconciling the results from free-air CO_2 enrichment studies with longer-term studies using ecosystem models to assess the importance of CO_2 fertilization relative to other disturbance regimes.

Randerson then addressed some of his own work on fires and their implications for the carbon cycle. He said that two-thirds of the CO_2 anomalies observed between 1997 and 2001 were caused by fire, although climate effects strongly influence the ability of humans to use fire as a method for land clearing. Randerson suggested that the primary climate factor regulating future carbon fluxes from terrestrial ecosystems is drought stress allowing fire use, rather than temperature stimulating increased microbial respiration. If the climate shifts to a more El Niño-like state, it will allow people living on the periphery of closed canopy forests to use fires to accelerate the rate of land clearing for agriculture. Thus, Randerson noted that fire emissions represent a combination of direct and indirect natural processes.

DATA AND ANALYSIS TOOL NEEDS

Data Needs for Partitioning Direct and Indirect Effects

Richard Birdsey, USDA Forest Service, discussed data needs for partitioning direct and indirect effects on the terrestrial carbon cycle. He characterized the most useful landscape datasets as the following:

- consistent vegetation classifications;
- land use/management, such as land cover, management intensity, and product harvesting;
- soil characteristics;
- topography;
- sediment and dissolved organic and inorganic carbon transport by rivers; and
- regional and local factors, such as natural disturbance, CO_2 concentrations in urban areas, and methane sources.

The most useful atmospheric datasets include:

- climate (e.g., temperature, precipitation, radiation, wind, extreme events);
- fossil fuel emissions;
- atmospheric composition (e.g., CO_2, Oxygen, nitrogen oxides); and
- air pollution (e.g., ozone, aerosols, wet and dry nitrogen deposition).

The following are the site specific datasets that Birdsey classified as essential for separating direct and indirect effects:

- species/biome response curves (e.g., growth response to CO_2 and nitrogen, carbon responses to management activities and land use by age class);
- soil responses to management and disturbance;
- land-atmosphere CO_2 exchange;
- long-term ecological and hydrological monitoring; and
- atmosphere/land/ocean boundaries.

He described these data as critical for parameterizing and validating models.

Birdsey approximated the availability of the required data for different terrestrial regions (see Table 3-2). Temperate forests, as one might expect, tend to have more information than tropical and boreal forests, but overall there is a variety of data and some areas need more attention than others. Nevertheless, he noted that these datasets are for a single point in time, yet often it is the frequency of data collection that is most critical.

The amount of data required depends on the scope at which the carbon budget is being examined (global, continent, country, region, local), the spatial resolution desired (grid size, geographical or political), and the temporal resolution. Carbon storage and exchange processes operate on a wide range of timescales, each of which needs to be considered to some extent.

Birdsey concluded with his sense of the level of spatial and temporal resolution that is realistic now and in the future. Currently carbon budgets can be constructed at the global scale or for large countries at a scale on the order of 5 to 50 kilometers, in increments of about 10 years. He also noted that scientists have a limited ability to partition some direct and indirect effects at this scale but not all. Birdsey speculated that in 10 years, the grid and temporal increments will come down to a grid scale of 1 to 5 kilometers in increments of 10 years or a grid scale of 5 to 50 kilometers in increments of 1 year due to the increased availability of datasets and improved computer processing capability. There should also be enhanced ability to partition effects. Birdsey predicted a trend of continuing improvement in temporal and spatial resolution as time continues.

TABLE 3-2 Availability of Data Needed to Separate Indirect and Direct Effects by Region

Data type	**Tropical**	**Temperate**	**Boreal**
Vegetation classification	***	***	***
Land use/management	*	**	*
Soils	*	**	*
Sediment	*	*	*
Regional/local factors	*	**	*
Climate	**	***	**
Fossil fuel emissions	***	***	***
Atmosphere composition	*	*	*
Air pollution	**	***	**
Site-specific data	*	**	*

NOTE: ***Data exist and are available; **data exist with gaps; *data are sparse.
SOURCE: Birdsey (2003).

Consideration of Spatial and Temporal Scales in Assessing Carbon Stocks and Fluxes

George Hurtt, University of New Hampshire, addressed spatial and temporal issues in the assessment of carbon stocks and fluxes. Relevant biological, biogeochemical, and atmospheric measurements are made on many different spatial scales (e.g., subcellular, leaf-level, plot level, regional) and temporal scales (e.g., diurnal, seasonal, decadal). Hurtt stated that one of the greatest challenges is to understand how all these different measurements can be treated and understood simultaneously. Accurate projections of future carbon dynamics over large scales depend on achieving this synthesis in models.

Hurtt emphasized that spatial and temporal heterogeneities have important implications to calculations of carbon stocks and fluxes. The landscape is incredibly heterogeneous due to variables such as topography, climate, soils, land use, fire, and even fine-scale dynamic heterogeneities, such as gaps in forest canopies. Carbon dynamics are strongly dependent on these heterogeneities. In addition, the harvesting and transport agricultural precuts (e.g., wood, crops) create important spatial considerations for carbon budgets, since decomposition might not match the pattern where the carbon is fixed. Fire and other disturbances can cause rapid temporal changes to ecosystem structure and carbon fluxes on the timescale of hours, thereby initiating a process of succession that can take years to centuries until full recovery. Most importantly, because most relevant biological processes are nonlinear, models based on average values of important underlying heterogeneities are likely to be highly inaccurate for long-term predictions.

Hurtt noted that there is a large and growing set of data that is important for characterizing the spatial and temporal scales of carbon stocks and fluxes and the mechanisms involved. Data come from a variety of sources (e.g., ground-based data, atmospheric data, remote sensing, experiments) and cover a range of scales. These measurements are increasing in frequency, resolution, and reliability. For example, targeted optical remote sensing observations are now available in resolutions of 1 meter or less, and important large-scale inventories, such as the U.S. Forest Inventory, are moving to provide annual statistics. Hurtt commented that it is important to continue to expand data collection while maintaining data continuity in order to examine future change.

Models are tools that can relate the observations collected from many different scales and platforms, including small-scale process studies, stand-scale inventories and flux measurements, and regional analyses such as from forest inventories, remote sensing, or atmospheric data. For a model to do this, it must represent all these different scales (including fine-scale heterogeneity) and the kinds of processes that occur at all levels. A model cannot simply average over the heterogeneity and then aggregate to project future conditions, at least over long periods of time. Hurtt noted that heterogeneity must first be resolved at a small scale in order for averaging to be correct.

Hurtt presented an example of the Ecosystem Demography (ED) model, which is a terrestrial biosphere model that links together phenomena operating at varying spatial and temporal scales. The spatial and temporal scales range from the detailed fast responses of plant physiology (occurring at the leaf level at an hourly timescale) through the slow changes in vegetation structure and below-ground carbon stores (occurring at the ecosystem level over centuries). It consists of a mechanistically driven individual-based vegetation model describing the growth, reproduction, and mortality dynamics of plant communities coupled to biogeochemical and hydrological models describing the associated below-ground fluxes of carbon, water, and nutrients. The components of ED draw heavily on established submodels developed by others over the past several decades to simulate plant functional types, gap dynamics, carbon and nutrient dynamics, and leaf-level photosynthesis and evapotranspiration. To run efficiently at large scales, the model uses a system of size- and age-structured equations to accurately approximate the consequences of the stochastic processes associated with forest dynamics.

Hurtt concluded that data are needed from multiple spatial, temporal, and biological scales to characterize the relevant patterns and processes over long periods of time and that despite recent progress, significant challenges remain to appropriately and efficiently synthesize these data into models that can accurately integrate across these multiple scales. He noted that models need to account for fine-scale heterogeneity in order to accurately simulate the nonlinear dynamics of the carbon cycle, and new modeling approaches are needed for representing heterogeneity in large-scale analyses (e.g., biodiversity, disturbance, or hydrological factors). Hurtt commented that the required resolution for input parameters of an inventory system depends strongly on the resolution desired for the inventory output. He suggested that formal network design studies be conducted to produce an efficient inventory system with known statistical properties.

U.S. Forests: Inventories, Ecosystem Models and Other Approaches

Linda Heath, USDA, discussed U.S. forest carbon measurement, focusing primarily on "bottom-up approaches." Heath said examining a number of smaller areas and summing them up for a total is an example of a bottom-up approach, which requires an explicit estimate for each area. For example, if the area and the carbon per area are known, they can be multiplied to determine the total carbon stock. Most inventories also need a remote sensing layer, which might be considered a top-down approach.

Heath reviewed the components of forest carbon, which include live and dead standing trees (and their roots), understory vegetation, down dead wood, and the litter layer. Harvested wood is also tracked in the following four categories: wood products in use (e.g., lumber, plywood), land-filled wood and paper, emissions from waste wood that is decayed or burned, and wood that is burned for energy.

Heath described the many sources of data for forest carbon inventories, including the Natural Resources Conservation Service's National Resource Inventory, the USDA Forest Service Forest Inventory and Analysis (FIA), and maps from the USGS. The FIA data include some information about ownership, which is important because the amount of carbon in the forests and the carbon being sequestered depends on forest management, which often depend on the owner. At a national level, plot-level database compilations exist for 1987, 1992, 1997, and 2002 and tree-level databases for 1997 and 2002. However, these databases may not all contain data from the same measurement year. For example, if a particular state did not conduct an inventory in 1992, the most recent year of data collection is included. Regional summaries of volume and area are also available by forest type and owner for the years 1953, 1963, and 1977.

The Environmental Protection Agency estimates that about 90 percent of the 0.225 Pg carbon sequestered as CO_2 due to land use change and forestry in 2001 was in forests (EPA, 2003). To produce those estimates, Heath and her team used FIA inventory data coupled with a modeling approach. The newer FIA annualized sampling design includes using remote sensing data to stratify forest area (Phase I), ground sampling of forest attributes (Phase II), and additional ground sampling on a subset of the plots (Phase III). A set of empirical or fundamental process models convert the inventory data to estimate forest carbon pools, and a forest sector model projects the estimates through 2050. Over the 1990s, Heath estimated that 70 percent of the carbon lost to disturbance effects was caused by wood harvests, a variable that could fluctuate substantially with price. In order to forecast carbon in future managed forests, several models are used, including a timber market model, a regulatory model, a paper market model, and ecosystem carbon models. Data on wood and paper production, exports and imports, years of wood product use, and disposal methods are also required (Skog and Nicholson, 1998).

Increasingly, states are moving to an annualized inventory. Typical inventory measurements include plot age, disturbance, owner, and elevation; tree species and dimensions; and Phase III measurements of dead wood, forest floor carbon, and soil carbon. Generalized equations are used to convert trunk diameter data to above-ground biomass for individual tree species (Jenkins et al., 2003). The inventory plots are located randomly in a hexagonal grid system in each state, and one-fifth of the plots are measured each year, such that each plot is inventoried every five years.

Whether inventory data can be used to distinguish direct and indirect land use effects, Heath remarked, depends on the definition of direct and indirect. If an indirect effect produces an attributable measurable effect by visual damage on ozone-sensitive plants, it could be possible to estimate the effect using inventory data, although some additional information from site-specific studies might be needed. She noted that while increased sequestration seems to receive the most emphasis in the assessment of indirect effects, it is probably easier to use inventory data to estimate negative, or decreased, sequestration indirect effects than positive ones.

Overall, Heath speculated that indirect effects are likely to be small relative to direct effects in most forestland in the conterminous United States, since these forests are directly affected by humans, past and present practices, management, land use change, and invasive species. In contrast, indirect effects in Alaskan forests may be more important since these areas are less affected by humans and grow slowly. Heath emphasized that resources are limited, and it is costly and complicated to measure carbon sequestration accurately, without trying to separate direct and indirect effects.

Heath concluded that a major strength of bottom-up inventory data is that they are a measured sample of reality, which is fairly transparent. They can be used as validated information for models, which can also capture economic effects. However, she stated that the current inventory system is very costly and was not originally designed to measure carbon. Design changes over time can also make the data analysis difficult. Heath estimated that uncertainties of five-year carbon sequestration calculations for the conterminous United States are ±50 percent (at a 95 percent confidence interval), and she suggested several research and data collection approaches that could reduce uncertainty. These include annualized FIA surveys in all 50 states, optimizing the surveys for forest carbon sequestration, and releasing requests for proposals on the topic of integrating approaches to reduce uncertainty.

In the discussion following Heath's presentation, Richard A. Houghton expressed concern that some types of land uses may be overlooked in the traditional inventory system and delegation of inventory responsibilities to a number of agencies. For example, Houghton stated that no agency is responsible for assessing woody encroachment, and he questioned what other carbon stocks may be falling through the cracks.

Tropical Forests: Inventories, Ecosystem Models, and Other Approaches

Sandra Brown, Winrock International, discussed the carbon budget of tropical forests with respect to bottom-up approaches. More than half the world's forest area is located in tropical forests—approximately 2 billion hectares in the 1990s. Brown noted that the tropical zone is considered one of the most uncertain biomes with respect to its role in the carbon cycle, since top-down and bottom-up approaches tend to yield conflicting conclusions regarding the role of the tropical zone as a carbon source or sink. Tropical forests are considered to possess sizable potential for carbon emissions mitigation if activities such as afforestation and reforestation of degraded lands are performed. Meanwhile, tropical deforestation has been estimated at 12 million to 14 million hectares per year during the 1990s (FAO, 2001).

Direct effects in tropical forests are due to changes in land use. One accounting model (Houghton, 1999) tracks land use change and the corresponding carbon stocks in the tropics through time, showing that roughly 2 Pg C/yr is removed due to tropical land use change. Brown commented that synthesis of ecological studies has generally been based on too few studies, which did not measure the carbon stocks in a systematic or robust way.

Tropical forest inventories, in contrast, tend to be well designed and conducted at an appropriate scale because many of them have been conducted to evaluate potential economic investments. However, there can be fairly incomplete inventory coverage, and sometimes these inventories focus only on a minimum tree diameter of 30 to 50 centimeters or only on commercially valuable species. Some inventories are several decades old and were not repeated on a regular basis. Nevertheless, means have been developed to convert inventory data into biomass data (e.g., Brown, 1997). Brown noted that inventory studies tend to result in lower biomass estimates than ecological studies, but she asserted that inventory data better represent the landscape at a larger scale.

In estimating carbon fluxes, Brown highlighted a concern about researchers' limited understanding of the forest carbon stocks where deforestation is occurring, based on little spatial representation of land use change. Some biomass maps are available that could, in theory, be combined with remote sensing data to produce a much better estimate of land use changes. Brown also noted that carbon flux estimates do not include forest degradation or fully account for the damage from logging on a residual stand, and she stated that rates of regrowth are not well known. Carbon flux calculations also assume that the forests are at a steady state during the simulation period.

Brown then described a study of forest degradation in Africa that suggests carbon sources due to land use change in the tropics may be underestimated. Gaston et al. (1998) measured actual biomass, based on an inventory and population density, and compared that to the expected biomass based on the biophysical characteristics of that area. The analysis showed a larger amount of carbon loss due to degradation than to deforestation. Brown further presented analyses from Malaysia that suggest deforestation is focused in areas with a lot of accessibility and fragmented landscapes (Brown et al., 1994). The loss of biomass in Malaysia is mostly from the removal of big trees, which can represent 30 percent of the biomass per hectare.

Several focal areas were presented for reducing uncertainty in estimates of tropical forest carbon fluxes. Brown suggested that better and more frequent assessments of carbon stocks and land use change be developed for vulnerable areas, with less emphasis on obtaining full coverage. Coarse resolution remote sensing may also be able to identify vulnerable areas for deforestation, while spatial models may be able to further identify drivers (e.g., access, fragmentation) of forest degradation. Brown also stated that more research to identify historical land use patterns and quantify forest degradation and fragmentation are needed to better understand changes in tropical forest carbon stocks.

Most of the work on indirect effects in tropical forests has utilized modeling (e.g., CO_2 effect studies by Tian et al., 1998; McKane et al., 1995; Potter et al., 1998). However, there have been a few experiments measuring carbon fluxes over different time frames in the Amazon. To resolve the uncertainties of indirect effects, Brown suggested the need for experiments on tropical forests to assess the effects of temperature, CO_2 enrichment, and nutrient deposition. Because half of the world's tropical forests are secondary forests, Brown suggested that experiments focus on them because the greatest indirect effects of CO_2 fertilization will be there. She also suggested that the network of older forest plots be expanded and that the ages of forest plots be more accurately determined.

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Summary of the State of the Science and Its Policy Implications

In the final discussion session of the workshop, the participants emphasized the need to describe what is known about direct and indirect carbon fluxes and what scientific advances are needed to address remaining uncertainties (see Chapter 1 for a discussion of the relevance and classification of direct and indirect human-induced effects). Eric Sundquist, U.S. Geological Survey, led a discussion to summarize the state of the science on quantifying a change in carbon stocks and partitioning the carbon fluxes by cause and the implications for policy makers. Sundquist stated that the current challenge is to address the scientific questions in ways that contribute to the information needs of the policy community.

The following section summarizes key findings from that discussion and from the workshop presentations and their relevance to policy concerns. The summary is organized according to the workshop goals originally presented in Chapter 1.

What methods are available for quantifying, characterizing, and cross-checking terrestrial carbon stocks over differing timescales and spatial scales?

Workshop participants noted that the landscape is incredibly heterogeneous due to variables such as topography, climate, soils, land use (both current and historical), and vegetation type and age distribution, and carbon dynamics are strongly dependent on these heterogeneities. Fire and other disturbances can cause rapid changes to carbon stocks on the timescale of hours, followed by years to centuries of recovery. Because most relevant biological processes are not additive, models based on average values of important underlying heterogeneities are likely to be highly inaccurate for long-term predictions.

Several presenters emphasized that multiple methods and investigations, including seemingly redundant cross-checks, are important to quantify biophysical and biogeochemical constraints on carbon storage. Multiple methods may include using trace gas inventories (through a “top-down” approach), biospheric inventories (through a “bottom-up” approach), field-scale experiments, and process studies (including process-based modeling that links together phenomena operating at varying spatial and temporal scales). For example, some biomass maps are available that could be combined with remote sensing data to produce a much better estimate of land use changes.

Workshop participants noted that there is a large and growing set of data important for characterizing carbon stocks and fluxes and the mechanisms involved over varying spatial and temporal scales, and these measurements are increasing in extent, resolution, and reliability. Nevertheless, several data needs were highlighted to improve the assessment of terrestrial carbon stocks. Some important factors identified include knowing the area over which the particular land use change is occurring and the time frame for the initial land use disturbance and recovery. Rates of regrowth are also not well understood. Methods proposed for obtaining such data include (1) high-resolution remote sensing to classify and map disturbance types, ages, and land-cover changes and (2) satellite lidar products to classify and map forest height and age. Comprehensive inventories of the tropical region were also suggested, with the greatest emphasis placed on vulnerable areas. To better understand changes in tropical forest carbon stocks, a workshop participant encouraged more research to identify historical land use patterns and quantify forest degradation and fragmentation, using spatial models to further identify drivers of forest degradation. Formal network design studies could develop efficient inventory systems with known statistical properties and protocols for monitoring and remote sensing. Workshop participants also suggested that policies be better able to accommodate future improvements in measurement technologies.

How do terrestrial carbon stocks and related greenhouse gas emissions change over time as a function of direct human-induced changes in land use, forestry, and other practices?

Workshop participants reported that the terrestrial carbon flux due to land use change is estimated to have totaled about 2.2 Pg C/yr during the 1990s. By far the largest source of carbon was the conversion of forest to cropland in tropical regions, followed by deforestation for pastures and logging. Tropical forests are considered to possess sizable potential for mitigation of carbon emissions if activities such as afforestation and reforestation of degraded lands are performed. One speaker reported that for the time period 2008 to 2012, afforestation and reforestation activities are expected to cause a sink totaling between 0.2 and 0.6 Pg C/yr worldwide, while deforestation is estimated to emit 1.8 Pg C/yr. Yet sizable uncertainty exists in data regarding land use changes and the carbon cycle, in both estimating total area changes and understanding the key factors controlling carbon storage.

Presenters discussed the effects of various management practices on carbon stocks, including afforestation, reforestation, deforestation, selective harvesting, conversion to no tillage agriculture, and fire management. While some effects have been consistently estimated in a range of experiments (such as the loss of soil carbon after agricultural cultivation), other effects varied based on species type, management practice, and age factors (e.g., the effects of forest harvest on soil carbon). Overall, speakers noted large uncertainty in the estimations of land use change and management effects on soil organic carbon stocks.

Afforestation following cropland uses was shown to increase soil organic carbon, and both fire suppression and afforestation can cause large increases in dead wood biomass and above-ground biomass. While the accumulation of dead wood biomass was shown in studies to plateau after the initial years of forest development, one speaker noted that above-ground biomass should not be assumed to plateau with age. It was noted that fire suppression can cause a forest to lose its resilience to a catastrophic fire, thereby causing a massive release of stored carbon and making the forest more vulnerable to a fire that completely alters the forest structure.

Workshop participants also addressed a closely related question:

What is the efficacy and longevity of various carbon storage practices and technology?

Several speakers noted that proper management of carbon sinks can deliver enormous atmospheric and social benefits. For example, Watson stated that 0.4 Pg C/yr could be taken up (mostly through agroforestry) by non-Annex I countries. Both the efficacy and the longevity of carbon storage practices depend greatly on previous land use history. Lands that lost more carbon due to previous land management have a greater potential to store carbon in the future, although soil carbon may reach a saturation point after a certain amount of time. Efficacy and longevity of carbon storage practices also depend on mean annual temperature, precipitation, and percent radiation.

Several specific carbon storage practices were discussed by workshop presenters. For example, one speaker described how selective cutting with fire management can produce the same amount of forest products as clear cutting while increasing above-ground forest carbon storage. Conversion to no tillage agriculture received extensive discussions. Several studies were presented that showed an increase in soil organic matter in the upper soil zone after conversion to no tillage practices. Additionally, no tillage agriculture minimizes soil erosion, further reducing carbon losses. Nevertheless, soil carbon pools can be filled over time, and the impact of conversion from conventional tillage to no tillage on soil carbon levels off after several decades. The carbon savings associated with decreased emissions, however, will continue as long as the no tillage management practice continues. In evaluating the efficacy of carbon storage practices, several participants expressed concern that the total costs of management be considered, including other greenhouse gas emissions and the carbon costs of fertilizer production or irrigation.

Although a number of studies were presented that showed the impacts of carbon storage practices, several participants expressed concern that the methods of estimating the direct effects due to management activities remain insufficient to meet policy needs. Although plot-scale experiments were presented to test the impact of management effects, Michael J. Prather commented that what is needed is the ability to predict carbon sequestration from a managed project, and he noted that based on what had been presented at the workshop, this capability does not exist.

In order to fully understand the longevity of carbon storage practices, long-term data will be needed in order to test hypotheses regarding the interactions among those processes. Several speakers emphasized the importance of extending the timescales of greenhouse gas research beyond what the policy community typically considers. Many carbon storage processes are inherently long term, and current human contributions to carbon storage are linked to historical information. Likewise, workshop speakers emphasized the importance of extending timescales of consideration with respect to greenhouse gas emissions management because the processes involved in carbon storage often have long-term management implications. The consideration of management options is inherently prognostic and requires an understanding of the long-term process.

How do terrestrial carbon stocks and related greenhouse gas emissions change over time as a function of indirect human-induced effects, natural effects, and past practices in forests and current or former agricultural lands?

Workshop participants noted that the residual terrestrial flux has been estimated at 2.9 Pg C/yr for the 1990s.[9] Participants noted, however, that there is sizable uncertainty in the current estimate of the residual sink, and current estimates of direct human-induced effects and past practices are too uncertain to estimate the magnitude of indirect effects. Workshop speakers confirmed that indirect human-induced effects can alter the timing and magnitude of emissions and removals, although some participants suggested that if the influence of past management changes on carbon fluxes could be accurately estimated, the indirect effects might appear insignificant.

The workshop discussions highlighted how indirect and natural effects are difficult to estimate and predict. Ecosystem functions can be random or probabilistic in nature, specifically with regard to fires, storms, insects, and mortality. Climate disturbances can have long-term nonlinear effects because of the different timescales of the processes affected. Nitrogen and CO_2 process interactions are not simply additive. These indirect factors interact with each other differently depending on precipitation, the plant community, and species-level changes.

Three specific indirect effects—nitrogen deposition, CO_2 fertilization, and climate effects—were discussed at the workshop. Speakers presented results from a forest CO_2 enrichment experiment showing substantial CO_2 stimulation in tree ring growth and relative basal area increment, although the tree ring growth exhibited declining growth response over time. The magnitude of CO_2 stimulation varied over time, and speakers noted that the influence of CO_2 enrichment on net primary productivity remains poorly understood. Deposition of combustion-related nitrogen oxides can also have a significant impact on the global carbon uptake, contributing an added sink of approximately 0.4 Pg C/yr. Climate change can also influence carbon fluxes, although one speaker suggested that the largest potential impact of climate change is drought stress, allowing increased use of fire for land clearing.

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[9] As noted in Chapter 1, the residual flux (or residual sink) is thought to originate from terrestrial processes and represents the apparent imbalance in global CO_2 accounting, shown below with estimates (in petagrams of Carbon per year) for the 1990s from Houghton (2003):

Atmospheric increase = Fossil fuel emissions + Terrestrial flux from land use activities
3.2 6.3 2.2
– Ocean uptake – Residual flux
2.4 2.9

Workshop participants noted that an improved understanding of indirect and natural effects and the role of past practices is necessary to quantify uncertainties in carbon emissions estimates for policy makers. Based on the observed behavior of natural and indirect effects, one speaker noted that greenhouse gas management and policies should accommodate random or probabilistic variability in carbon storage.

What methods are available to distinguish direct human-induced changes in terrestrial carbon stocks and related greenhouse gas emissions from those caused by indirect human-induced effects, natural effects, and effects due to past practices in forests and current or former agricultural lands?

Workshop participants suggested a progression of approaches that could be used for estimating direct effects and potentially developed for separating those effects from indirect human-induced effects, natural effects, and effects due to past land use practices:

- *Inventory data analysis* enables estimations of the areas over which direct effects are taking place and the amount of carbon change per unit area. Indirect effects could potentially be estimated by this approach if the effect produces an attributable, measurable effect by visual damage (e.g., on ozone-sensitive plants). Several workshop participants highlighted concerns with the level of temporal and spatial detail in current inventory data and knowledge of land use and cultivation history.
- *Standard values* (or rules of thumb) represent the community's consensus about how these processes work. Standard values, however, have limited accuracy and are less successful in describing regional variations or deviations in management practice.
- *Control plot studies* can determine the effects of management where both treatments are influenced by indirect effects and natural variation. Nevertheless, workshop participants debated the potential for scaling plot-level data to larger landscapes.
- *Multifactor manipulations* represent experiments for testing management schemes over many decades (e.g., CO_2 enrichment experiments). Nevertheless, there are difficulties with controlling all of the influencing factors, including the impacts of past practices, in multifactor manipulation.
- *Bottom-up models* are based on relevant processes that could, in principle, be validated. However, current models do not include all the important processes, and they are not accurate at all the relevant scales.
- *Top-down models* are based on large-scale processes and aggregate data, enabling the development of a spatial map of carbon fluxes

attributable to each of the major mechanisms, such as fire or tropical regrowth. Workshop participants noted that top-down models are influenced by initial estimates.

Workshop participants also discussed the feasibility and practicality of separating direct and indirect human-induced effects. Many participants expressed the opinion that a quantitative separation of direct and indirect effects in any detail is not practical at this time, and if it were required as part of national inventories, it would add significantly to the reporting costs. Participants also noted that more research and data are needed to separate indirect and direct effects, including improvements in the abilities to measure effects on carbon fluxes. Ian Roy Noble asserted that establishing a baseline—in the absence of indirect or management effects—was not possible at this time, at least to any significantly accurate level. Plot-scale experiments can be used to separate some effects, such as the effects of afforestation from past management effects. However, participants acknowledged that management effects could not be determined in the absence of indirect effects. Others asserted that CO_2 and nitrogen fertilization effects or species changes could not be separated out quantitatively at this time, considering the many nonadditive effects that have been observed. Field noted that separating random effects from management impacts will not be possible, over economically and ecologically meaningful domains of space and time.

Concerns were also raised about the time frame over which indirect and direct effects could be separated. In order to be relevant to the Kyoto Protocol, controlled experiments would be needed that retrospectively separate management effects from indirect effects back to the year 1990. Such a retrospective separation of effects involves huge challenges. Others questioned whether terrestrial uptake caused by pre-1989 land use changes can be factored out with existing scientific capabilities. One participant suggested developing a bold new approach to study the consequences of different management regimes and strategies, analogous to Long Term Ecological Research sites.

The issue of spatial scaling in the separation of direct and indirect effects was also addressed. Several participants noted that “top-down” estimates of indirect effects do not agree with estimates from scaling plot-level data and urged more research attention to the convergence of the plot-level and global scales. However, others suggested that it would be prohibitively expensive to design and conduct the controlled experiments for a precise bottom-up approach.

Many speakers articulated the need for a broad ecosystem perspective, since many of the relevant processes are interactive and involve other components of the system besides carbon. Carbon exchange effects (including direct and indirect effects) are inherently interactive, and carbon management decisions are rarely made in isolation from other resource management concerns. Workshop participants said that full carbon accounting inherently requires a broad ecosystem perspective, can help reduce uncertainty, and can make discrimination of management effects more practical in some ways.

While the above methods were not considered to be adequately developed for separation of direct, indirect, and natural effects at this time, several workshop participants expressed optimism that over the next decade or so information from these methods could provide reasonable constraints on estimates of these processes.

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Acronyms and Abbreviations

CDM	Clean Development Mechanism Kyoto Protocol
CMR	carbon management response
COP	Conference of the Parties
CTIC	Conservation Technology Information Center
ED	Ecosystem Demography
EPA	U.S. Environmental Protection Agency
FACTS	Forest-Atmosphere Carbon Transfer and Storage
FAO	Food and Agriculture Organization of the United Nations
FIA	Forest Inventory and Analysis (U.S. Forest Service)
GPP	gross primary production
Gt	gigaton
ha	hectare
IPCC	Intergovernmental Panel on Climate Change
LULUCF	land use, land use change, and forestry
Mg	megagram
Mt	megatons
NASA	National Aeronautics and Space Administration
NEE	net ecosystem exchange
NEP	net ecosystem production

NOAA	National Oceanic and Atmospheric Administration
NPP	net primary production
NRI	National Resource Inventory
Pg	petagram
ppm	parts per million
SBSTA	Subsidiary Body for Scientific and Technical Advice
Tg	teragram
UNFCCC	United Nations Framework Convention on Climate Change
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
yr	year

Appendix A
Agenda

A National Academies Workshop

DIRECT AND INDIRECT HUMAN CONTRIBUTIONS TO TERRESTRIAL GREENHOUSE GAS FLUXES

The National Academies
Keck Center, Room 100
500 Fifth St., NW
Washington, DC 20001
September, 23-24, 2003
8:00 am to 5:30 pm

September 24th, 2003
Keck Center, Room 100

8:00 a.m.	Breakfast – Room 100
8:30	Introductory Remarks: Goals and Statement of Work, Definitions, Product of Workshop *Michael Prather, Chair*
8:45	Sponsor Perspective *William Hohenstein, USDA Global Change Program Office*

9:10	Terrestrial Ecosystems, Carbon Stocks, and the UNFCCC *Bob Watson, World Bank*
9:40	Discussion *Ian Roy Noble, World Bank*
10:30	Break
11:00	National and International Greenhouse Gas Inventory System: Technical Requirements, Project Accounting, and Uncertainty *Dina Kruger, EPA*
11:30	Discussion *John Kimble, USDA/Natural Resources Conservation Service*
12:00 p.m.	Lunch — Room 100
1:30	Consideration of Spatial Scales and Timescales in Assessing Carbon Stocks and Fluxes *George Hurtt, University of New Hampshire*
1:50	Separating Direct Human-Induced Changes from Other Effects *Jen Jenkins, University of Vermont (presented by Richard Birdsey)*
2:10	Discussion *Ann Camp, Yale University*
2:30	Break
3:00	Estimates of Carbon Stocks and Fluxes from Land Use Change *Christine Goodale, Woods Hole Research Center*
3:30	Estimates of Carbon Stocks and Fluxes from Forestry Activities *Evan DeLucia, University of Illinois Urbana-Champagne*
3:50	Estimates of Carbon Stocks and Fluxes from Agricultural Activities *Cesar Izaurralde, Battelle, Pacific Northwest National Laboratory*
4:20	Discussion *Perry Hagenstein*
4:50	Summary of Key Issues, General Discussion *Richard Houghton, Woods Hole Research Center*
5:30	Wrap-up and Adjourn for the Day *Michael Prather, Chair*

September 24, 2003
Keck Center, Room 201

8:00 a.m.	Breakfast — Room 208
8:30	Carbon Cycle — Overview of CO_2 and CH_4 cycles *William Schlesinger, Duke University*
9:00	Indirect Human-Induced Effects (CO_2 fertilization, nitrogen, climate change) *Dennis Ojima, Colorado State University*
9:30	Natural Effects (fire, pests, and climate variability) *Nate Stephenson, USGS West Ecological Research Center, Sequoia and Kings Canyon*
10:00	Discussion *Ruth Defries, University of Maryland*
10:20	Break
10:40	Efficacy and Longevity of Varying Carbon Storage Practices *Tristram West, Oak Ridge National Laboratory*
11:10	Implications for Indirect and Natural Effects on National and International Greenhouse Gas Inventories *Chris Field, Carnegie Institution*
11:40	What Research is Needed to Enable Partitioning of Direct and Indirect Effects? *Jim Randerson, University of California, Irvine*
12:10 p.m.	*Discussion* *Jason Hamilton, Ithaca College*
12:30	Lunch — Room 208
1:30	Land Succession Effects (historical forest practices, agriculture to forests) *Chris Potter, NASA Ames*
2:00	U.S. Forests: Inventories, Ecosystem Models, and Other Approaches *Linda Heath, USDA*
2:30	Tropical Forests: Inventories, Ecosystem Models, and Other Approaches ***Sandra Brown,** Winrock International*
3:00	Discussion *Ian Roy Noble, World Bank*

3:20	Break
3:40	What Data Resolution for Direct and Indirect Effects? When Can This Be done? *Richard Birdsey, USDA Forest Service*
4:10	Issues of Scientific Methodology — Lessons from the UNFCCC Brazil Proposal *Michael Prather, University of California, Irvine*
4:20	Current State of the Science Regarding Partitioning of Net Carbon Fluxes *Eric Sundquist*
5:20	Anticipated Future Capability (Climate Change Science Program / Water Resources Applications Project) to Quantify Specific Processes *Bryan Hannegan, Council on Environmental Quality*
6:20	Wrap-up and Our Report
6:30	Adjourn

Appendix B

Steering Committee and Speaker Biographies

Richard Birdsey is the program manager for global change research at the USDA Forest Service Northeastern and North Central research stations. He is a specialist in quantitative methods for large-scale forest inventories and was a pioneer in the development of methods to estimate national carbon budgets for forestlands from forest inventory data. In his role as program manager, he is coordinating a national effort to improve the inventory and monitoring of forest carbon, to identify forest management strategies to increase carbon sequestration, to understand and quantify the prospective impacts of climate change on U.S. forests and forest products, and to develop adaptation strategies.

Sandra Brown is a senior program officer in the Ecosystem Services Unit at Winrock International and has spent more than 20 years conducting research on the role of forests in the global carbon cycle. Prior to joining Winrock she was a professor at the University of Illinois for 18 years. She received her B.Sc. in chemistry from the University of Nottingham, England, her M.S. in engineering sciences from the University of South Florida; and her Ph.D. in ecological engineering/systems ecology from the University of Florida, Gainesville.

Ann Camp is a lecturer and associate research scientist in the School of Forestry and Environmental Studies at Yale University. Prior to this position, she was a research forester at the USDA Forest Service's Pacific Northwest Research Station. Her research includes the effects of biotic and abiotic disturbances on vegetation patterns at stand and landscape scales; interactions among disturbance agents and vegetation patterns, especially the roles of insects and pathogens in creating forest structures important to wildlife; management alternatives for dense, marginally economic stands of small-diameter trees; and the consequences of different management practices on ancillary forest resources. She is also interested in the ways climate change will affect forest development as mediated through impacts on individual tree species and amplified by disturbances such as fires and insect outbreaks. Dr. Camp received her B.S. from Rutgers University, M.F.S. from Yale University, and Ph.D. in silviculture and forest protection from the University of Washington.

Ruth DeFries is an associate professor at the University of Maryland, College Park; with joint appointments in the Department of Geography and the Earth System Science Interdisciplinary Center. Her research investigates the relationships between human activities, the land surface, and the biophysical and biogeochemical processes that regulate the Earth's habitability. She is interested in observing land cover and land use change at regional and global scales with remotely sensed data and exploring the implications for ecological services such as climate regulation, the carbon cycle, and biodiversity. She previously was employed by the National Research Council. Dr. DeFries obtained a Ph.D. from the Department of Geography and Environmental Engineering at Johns Hopkins University and a bachelor's degree from Washington University with a major in earth science.

Evan DeLucia is a professor of plant biology at the University of Illinois, Urbana-Champaign, where he also serves as head of the Department of Plant Biology. After completing his B.A. at Bennington College and serving as a teaching fellow at Phillips Andover Academy, he received an M.F.S. from Yale and a Ph.D. from Duke. The adaptive physiology of trees and the role of forests in the global carbon cycle are at the center of Dr. DeLucia's research interests.

Christopher Field is director of the Carnegie Institution's Department of Global Ecology and professor by courtesy in the Department of Biological Sciences at Stanford University. Trained as an ecologist, Field has conducted environmental research from tropical rainforests to deserts to alpine tundra. He is a specialist in global change research. An author of more than 100 scientific papers, Field is a member of the National Academy of Sciences and a leader in several national and international efforts to provide the scientific foundation for a sustainable future.

Christine Goodale is an assistant professor in the Department of Ecology and Evolutionary Biology at Cornell University. Goodale was previously a postdoctoral fellow at the Woods Hole Research Center and the Carnegie Institute of Washington. Her research interests include land use history and forest carbon and nitrogen cycling. She received her Ph.D. and M.S. in natural resources from the University of New Hampshire and an A.B. in biology/geography from Dartmouth College.

Perry R. Hagenstein is a consultant on resource economics and policy and president of the Institute for Forest Analysis, Planning, and Policy, a nonprofit research and education organization. Previously, he was executive director of the New England Natural Resources Center and served as a Charles Bullard Research Fellow at the John F. Kennedy School of Government at Harvard. He also served as senior policy analyst for the U.S. Public Land Law Review Commission and was a principal economist for the USDA Forest Service. Dr. Hagenstein received his B.S. from the University of Minnesota, M.F. from Yale University, and Ph.D. in forest and natural resources economics from the University of Michigan.

Jason G. Hamilton is an assistant professor in the Department of Biology at Ithaca College. He received a Ph.D. in plant ecology (1997) and a Ph.D. in physical chemistry (1991) from the University of California, Santa Barbara. Hamilton is currently conducting research on the effects of elevated atmospheric CO_2 on forest ecosystem function and production and the interactions among altered atmospheric composition, leaf herbivores, and leaf physiological function in forest agricultural systems.

Bryan Hannegan is associate director for energy and transportation at the White House Council on Environmental Quality, where he coordinates federal environmental efforts in the areas of energy, climate change (science and technology), and transportation. Prior to joining the Executive Branch, Hannegan served as staff scientist for the U.S. Senate Committee on Energy and Natural Resources, where he was the principal staff member for national energy policy, energy efficiency, renewable energy, and climate change policy. He holds a Ph.D. in earth system science and an M.S. in mechanical engineering from the University of California at Irvine and a B.S. in meteorology from the University of Oklahoma.

Linda S. Heath is a project leader and research scientist with the USDA Forest Service Northeastern Research Station, Forest Carbon Dynamics and Estimation Research Work Unit in Durham, New Hampshire. She has worked for 10 years in the area of modeling carbon storage and flux between terrestrial ecosystems and the atmosphere for forests and forest products of the United States using models and forest inventory data. Heath is currently a lead author on the Intergovernmental Panel on Climate Change activity on Good Practice Guidance for Greenhouse Gas Inventories and is the criterion lead for carbon for the Interagency "State of the Nation's Forest" report addressing the Montreal Process Criteria and Indicators of Sustainability for U.S. forests. She has a doctorate in quantitative resources management from the University of Washington and degrees in forestry and forest management from the University of Illinois.

William Hohenstein is director of U.S. Department of Agriculture's Global Change Program Office, Office of the Chief Economist. The Global Change Program Office provides coordination and policy development support. It serves as the focal point for all support to the secretary of agriculture on the causes and consequences of global change, as well as strategies for addressing them. Before becoming director, Mr. Hohenstein served as a division director in Environmental Protection Agency's PA's National Center for Environmental Economics. He also represented the United States at several international negotiations on climate change and served as a U.S. representative to the Intergovernmental Panel on Climate Change.

Richard A. Houghton is a senior scientist at the Woods Hole Research Center. His research interests include the global carbon cycle, the effects of land use change on carbon storage, and the interaction between terrestrial ecosystems and climate. He has participated in all of the Intergovernmental Panel on Climate Change Assessments on Climate Change and the IPCC Special Report on Land Use, Land Use Change, and Forestry. He received his Ph.D. in ecology from the State University of New York at Stony Brook in 1979.

George Hurtt is an assistant professor at the University of New Hampshire's Institute for the Study of Earth, Oceans, and Space. He earned a B.A. in biology from Middlebury College, an M.S. from the University of Connecticut, and an M.A. and a Ph.D. in ecology and evolutionary biology from Princeton University. His current research is focused on the development and application of a new terrestrial ecosystem model that essentially takes a "statistical mechanics" approach to scaling local dynamics to global scales. Hurtt is involved in several collaborative research projects including the Large Scale Biosphere-Atmosphere Experiment in South America, an interdisciplinary science investigation using National Aeronautical and Space Administration's Earth Observing System, and efforts to develop global carbon system and land surface models. He is a coauthor and scientific spokesperson for the New England Regional Assessment of the Potential Consequences of Climate Variability and Change and has testified to both the New Hampshire Legislature and Congress on the science of global change.

Cesar Izaurralde is a staff scientist with the Joint Global Change Research Institute, a collaboration between Pacific Northwest National Laboratory (PNNL) and the University of Maryland. His research focuses are in the areas of modeling the impacts of climate change and variability on terrestrial ecosystems and water resources and carbon sequestration in, and greenhouse gas emissions from, agricultural soils. Previously Izaurralde served as chair of resource conservation with the Department of Renewable Resources, University of Alberta, Canada. In his native country of Argentina, he studied at and later joined the Facultad de Ciencias Agropecuarias at la Universidad Nacional de Cordoba. Izaurralde has received two PNNL Outstanding Performance Awards (1999, 2002) and a Fulbright fellowship (1980-1981). He was an invited professor at la Universidad Nacional de Cordoba (1996, 1999) and at la Universidad Catolica de Cordoba (1977-1980), both in Argentina. He holds adjunct appointments with the Departments of Natural Resource Sciences and Geography at the University of Maryland.

Jennifer C. Jenkins is a visiting assistant professor at the Gund Institute for Ecological Economics at the University of Vermont. His current research relates to developing and implementing methods for large-scale assessment of forest and nonforest carbon cycling and sequestration rates. Recent projects have included using monitoring and inventory data, remote sensing, ecosystem modeling, and field techniques to understand and predict terrestrial carbon cycles in the northeastern United States and mid-Atlantic regions. Jenkins previously was a research forester with the USDA's Forest Service. She received a Ph.D. in ecosystem ecology from the University of New Hampshire, a master's of forest science from Yale University, and a B.A. in biology with certificates in Environmental Studies and Education from Dartmouth College.

John M. Kimble is a research soil scientist at the National Soil Survey Center, Soil Survey Division, with the U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS). He received his B.S. in agronomy-soils from Ohio State University and his M.S. and Ph.D. in soil chemistry from the University of Vermont. He has been active in the soil global climate-change related activities at NRCS for about 15 years. His interests have focused on the measurement and verification of soil carbon (soil organic carbon and soil inorganic carbon), agronomic practices that help to increase carbon sequestration, and procedures used to scale point data to larger areas. Currently he is a member of the Council of the International Union of Soil Sciences (IUSS) and a member its Executive Committee. He has represented the IUSS to the International Geosphere – Biosphere Programme and many other international groups. He has been active in the Intergovernmental Panel on Climate Change (IPCC), contributed to the special report related to the Kyoto Protocol, and was a member of U.S. National Assessment's agriculture team.

Dina Kruger is chief of the methane and sequestration branch for the U.S. Environmental Protection Agency in the Voluntary Programs Division. She is responsible for managing voluntary programs aimed at reducing methane emissions from landfills, coal mines, the natural gas system, and agricultural sources. She also manages the agency's work in the area of carbon sequestration in forests and agricultural lands and a variety of economic and policy projects related to non-CO_2 greenhouse gases. She currently serves as the U.S. government representative to the IPCC Task Force Bureau on Greenhouse Gas Emission Inventories and served as co chair of the IPCC's recently completed report, *Good Practice in Greenhouse Gas Emission Inventories*. Ms. Kruger has an M.A. from the Energy and Resource Group at the University of California, Berkeley, and received her B.A. from the University of Washington.

Ian Roy Noble is a senior advisor at the World Bank on carbon sequestration through land use, land use change, or forestry activities and on adaptation to climate change. He is on secondment from his position as professor of global change research at the Australian National University. His research has focused on ecosystem dynamics and applying results to land management and sustainable development. He is past chair of the International Geosphere-Biosphere Programme's Global Change and Terrestrial Ecosystems and served as a senior author and editor of several assessments by the Intergovernmental Panel on Climate Change. He obtained his Ph.D. in modeling arid grazing systems from the University of Adelaide, South Australia.

Dennis Ojima is a senior research scientist at the Natural Resource Ecology Laboratory and an assistant professor in the Rangeland Ecosystem Science Department at Colorado State University. In 1999 he was selected as an Ecological Society of America's Aldo Leopold Leadership Fellow and contributed to several chapters of the 1995 Intergovernmental Panel on Climate Change. Previously, he was a program officer with the International Geosphere-Biosphere Program. His research activities address ecological issues related to global and regional land use and climate changes on ecosystem dynamics, studies of the interaction between terrestrial ecosystems and the atmosphere, the impact of changes in land management on trace gas exchange, and the development of a global ecosystem model. Ojima received his B.A. and M.S. in botany from Pomona College and the University of Florida and his Ph.D. from the Rangeland Ecosystem Science.

Christopher Potter is a research scientist with the Ecosystem Science and Technology Branch of the National Aeronautics and Space Administration's Ames Research Center. He came to NASA as a National Research Council associate. He and his colleagues were awarded the agency's Public Service Medal for development of the first computer model for global ecosystem exchange of all major biogenic trace gases with the atmosphere. He holds a Ph.D. and a master's degree in forest ecology from Emory University. He is the author of more than 50 peer-reviewed journal articles and numerous book chapters. He currently serves on scientific steering committees for NASA earth science planning and field campaign implementation.

Michael J. Prather is professor and Kavli chair in the earth system science department at the University of California, Irvine. He received his Ph.D. in astronomy and physics from Yale University in 1976. Prather has played a significant role in the International Panel on Climate Change's second and third assessments and special report on aviation and in the World Meteorological Organization's ozone assessments (1985-1994). He is a fellow of the American Geophysical Union and a foreign member of the Norwegian Academy of Science and Letters and has served on several National Research Council committees, including the Committee for Review of the U.S. Climate Change Science Program Strategic Plan and the Panel on Climate Variability on Decade-to-Century Timescales.

James T. Randerson is an assistant professor with the Department of Earth System Science, University of California, Irvine. Randerson is a biogeochemist interested in global carbon and nutrient cycles and uses atmospheric trace gas observations, satellite data, and models to study the biosphere. He is currently investigating pathways of rapid carbon loss from terrestrial ecosystems including fire emissions and permafrost degradation. He received a Ph.D. in biological sciences and a B.S. in chemistry from Stanford University.

William H. Schlesinger is James B. Duke Professor of Biogeochemistry and dean of the Nicholas School of the Environment and Earth Sciences at Duke University. Schlesinger received his A.B. from Dartmouth and Ph.D. from Cornell. He is the author or coauthor of over 150 scientific papers and a widely adopted textbook, *Biogeochemistry: An Analysis of Global Change* (Academic Press, 2nd ed., 1997). He was elected a member of the American Academy of Arts and Sciences in 1995 and the National Academy of Sciences in 2003. He has testified before U.S. House and Senate committees on a variety of environmental issues, including preservation of desert habitats and global climate change. Schlesinger was elected president of the Ecological Society of America for 2003-2004.

Nathan L. Stephenson is a research ecologist with the U.S. Geological Survey's Western Ecological Research Center. Previously, he worked as an ecologist at the National Park Service, establishing a long-term research program as a "place-based" scientist in the Sierra Nevada. His research interests include the climatic controls of forest dynamics, carbon dynamics, and vegetation distribution. Stephenson received his Ph.D. in plant ecology from Cornell University.

Eric Sundquist is a research geologist at the U.S. Geological Survey where he conducts research on relationships between global carbon cycle and atmospheric carbon dioxide. His current research interests include past natural variations in atmospheric carbon dioxide, relationships between oceanic and terrestrial carbon cycling, effects of human land use on carbon dioxide, effects of erosion and sediment transport on carbon dioxide budgets, and exchange of carbon dioxide between soils and the atmosphere. Sundquist received his Ph.D. and A.M. in geology from Harvard University and his B.A. in geology from Pomona College. He is currently on the Climate System Model Advisory Board at of the National Center for Atmospheric Research, is chair of the Committee on Global Environmental Change at the American Geophysical Union, and is a member of the U.S. Carbon Cycle Scientific Steering Group.

Robert T. Watson is the World Bank's senior spokesperson on climate change. He joined the bank in 1996 as senior scientific advisor in the environment department and was later appointed director of the same department. He is now the bank's chief scientist and was formerly chairman of the Intergovernmental Panel on Climate Change. Before joining the World Bank, he was associate director for environment in the Office of Science and Technology Policy, Executive Office of the President. Prior to joining the Clinton White House, he was director of the science division and chief scientist for the Office of Mission to Planet Earth at the National Aeronautics and Space Administration. Mr. Watson has played a key role in the negotiation of global environment conventions and the evolution of the Global Environment Facility.

Tristram West is a research scientist at Oak Ridge National Laboratory and a participant in the Department of Energy's Consortium for Enhancing Carbon Sequestration in Terrestrial Ecosystems. He received a B.S. in agriculture from the University of Kentucky and an M.S. and a Ph.D. in natural resources and agronomy from Ohio State University. West studies changes in terrestrial carbon dynamics associated with changes in land use and management and also the impact of carbon sequestration policies on net greenhouse gas emissions. His current research includes the global quantification of carbon accumulation and loss rates associated with a number of terrestrial carbon sequestration options. West collaborates with a number of federal, state, and academic organizations, and he has published several papers on terrestrial carbon sequestration and full carbon accounting.

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