4

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.

---

[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.