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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

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[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

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[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)

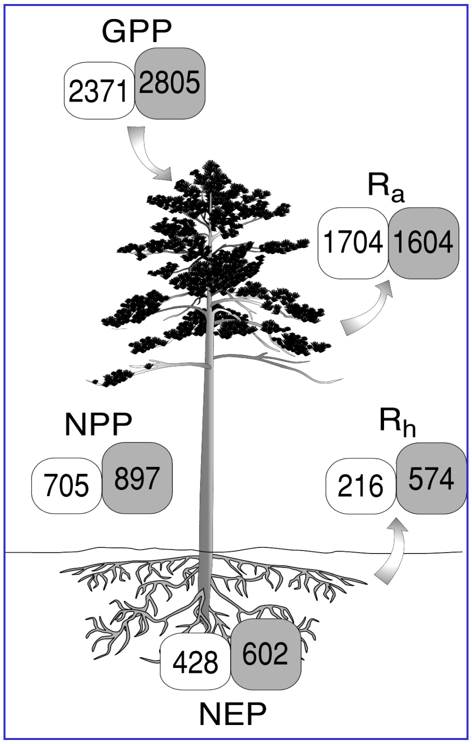

FIGURE 3-2 Carbon budget for a pine forest under CO_2 enrichment in the FACTS-1 experiment. Open bubbles represent ambient plots; closed bubbles represent elevated atmospheric CO_2 plots. Units are expressed in grams of carbon per meter^2 per year. GPP represents annual photosynthesis; respiration from 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.