Chapter 11. North American Forests

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KEY FINDINGS

- North American forests contain more than 170 Gt of carbon, of which 28% is in live biomass and 72% is in dead organic matter.
- North American forests were a net carbon sink of approximately -269 Mt C yr^{-1} over the last 10 to 15 years. This estimate is highly uncertain.
- Deforestation continues in Mexico where forests are a source of CO_2 to the atmosphere. Forests of the United States and parts of Canada have become a carbon sink as a consequence of the recovery of forests following the abandonment of agricultural land.
- Carbon dioxide emissions from Canada's forests are highly variable because of interannual changes in area burned by wildfire.
- The size of the carbon sink in U.S. forests appears to be declining based on inventory data from 1952 to the present.
- Many factors that cause changes in carbon stocks of forests have been identified, including land-use change, timber harvesting, natural disturbance, increasing atmospheric CO_2, climate change, nitrogen deposition, and tropospheric ozone. There is a lack of consensus about how these different natural and anthropogenic factors contribute to the current sink, and the relative importance of factors varies geographically.
- There have been several continental- to subcontinental-scale assessments of future changes in carbon and vegetation distribution in North America, but the resulting projections of future trends for North American forests are highly uncertain. Some of this is due to uncertainty in future climate, but there is also considerable uncertainty in forest response to climate change and in the interaction of climate with other natural and anthropogenic factors.

- Forest management strategies can be adapted to manipulate the carbon sink strength of forest systems. The net effect of these management strategies will depend on the area of forests under management, management objectives for resources other than carbon, and the type of disturbance regime being considered.
- Decisions concerning carbon storage in North American forests and their management as carbon sources and sinks will be significantly improved by (1) filling gaps in inventories of carbon pools and fluxes, (2) a better understanding of how management practices affect carbon in forests, (3) better estimate of potential changes in forest carbon under climate change and other factors, and (4) the increased availability of decision support tools for carbon management in forests.

INTRODUCTION

The forest area of North America totals 771 million hectares, 36% of the land area of North America and about 20% of the world's forest area (Food and Agriculture Organization 2001) (see Table 11-1). About 45% of this forest area is classified as boreal, mostly in Canada and some in Alaska. Temperate and tropical forests constitute the remainder of the forest area.

Table 11-1. Area of forest land by biome and country, 2000 (1000 ha).

North American forests are critical components of the global carbon cycle, exchanging large amounts of CO_2 and other gases with the atmosphere and oceans. In this chapter we present the most recent estimates of the role of forests in the North American carbon balance, describe the main factors that affect forest carbon stocks and fluxes, describe how forests the carbon cycle through CO_2 sequestration and emissions, and discuss management options and research needs.

CARBON STOCKS AND FLUXES

Ecosystem Carbon Stocks And Pools

North American forests contain more than 170 Gt of carbon, of which 28% is in live biomass and 72% is in dead organic matter (Table 11-2). Among the three countries, Canada's forests contain the most carbon and Mexico's forests the least.

Table 11-2. Carbon stocks in forests by ecosystem carbon pool and country (Mt C).

Carbon density (the amount of carbon stored per unit of land area) is highly variable. In Canada, the majority of carbon storage occurs in boreal and cordilleran forests (Kurz and Apps, 1999). In the U.S., forests of the Northeast, Upper Midwest, Pacific Coast, and Alaska (with 14,000 Mt C) store the most carbon. In Mexico, temperate forests contain 4,500 Mt C, tropical forests contain 4,100 Mt C, and semiarid forests contain 5,000 Mt C.

Net North American Forest Carbon Fluxes

According to nearly all published studies, North American lands are a net carbon sink (Pacala *et al*., 2001). A summary of currently available data from greenhouse gas inventories and other sources suggests that the magnitude of the North American forest carbon sink was approximately –269 Mt C yr^{-1} over the last decade or so, with U.S. forests accounting for most of the sink (Table 11-3). This estimate is likely to be within 50% of the true value.

Table 11-3. Change in carbon stocks for forests and wood products by country (Mt C yr^{-1}).

Canadian forests were estimated to be a net sink of -17 Mt C yr^{-1} from 1990-2004 (Environment Canada, 2006) (Table 11-3). These estimates pertain to the area of forest considered to be "managed" under international reporting guidelines, which is 82% of the total area of Canada's forests. The estimates also include the carbon changes that result from land-use change. Changes in forest soil carbon are not included. High interannual variability is averaged into this estimate—the annual change varied from approximately -50 to +40 between 1990 and 2004. Years with net emissions were generally years with high forest fire activity (Environment Canada, 2006).

Most of the net sink in U.S. forests is in aboveground carbon pools, which account for –146 Mt C yr^{-1} (Smith and Heath, 2005). The net sink for the belowground carbon pool is estimated at –90 Mt C (Pacala *et al*., 2001). The size of the carbon sink in U.S. forest ecosystems appears to have declined slightly over the last decade (Smith and Heath, 2005). In contrast, a steady or increasing supply of timber products now and in the foreseeable future (Haynes, 2003) means that the rate of increase in the wood products carbon pool is likely to remain steady.

For Mexico, the most comprehensive available estimate for the forest sector suggests a source of +52 Mt C per year in the 1990s (Masera *et al*., 1997). This estimate does not include changes in the wood products carbon pool. The main cause of the estimated source is deforestation, which is offset to a much lesser degree by restoration and recovery of degraded forestland.

Landscape-scale estimates of ecosystem carbon fluxes reflect the dynamics of individual forest stands that respond to unique combinations of disturbance history, management intensity, vegetation, and site characteristics. Extensive land-based measurements of forest/atmosphere carbon exchange for forest stands at various stages of recovery after disturbance reveal patterns and causes of sink or source strength, which is highly dependent on time since disturbance. Representative estimates for North America are summarized in Appendix 11.A.

TRENDS AND DRIVERS

Overview of Trends and Drivers of Change in Carbon Stocks

Many factors that cause changes in carbon stocks of forests and wood products have been identified, but the importance of each is still debated in the scientific literature (Barford *et al*., 2001; Caspersen *et al*., 2000; Goodale *et al*., 2002; Korner, 2000; Schimel *et al*., 2000). Land-use change, timber harvesting, natural disturbance, increasing atmospheric CO_2, climate change, nitrogen deposition, and tropospheric ozone all have effects on carbon stocks in forests, with their relative influence depending on geographic location, the type of forest, and specific site factors. It is important for policy implementation and management of forest carbon to separate the effects of direct human actions from natural factors.

The natural and anthropogenic factors that significantly influence forest carbon stocks are different for each country, and still debated in the scientific literature. Natural disturbances are significant in Canada, but estimates of the relative effects of different kinds of disturbance are uncertain. One study estimated that impacts of wildfire and insects caused emissions of about +40 Mt C yr^{-1} of carbon to the atmosphere over the two decades (Kurz and Apps, 1999). Another study concluded that the positive effects of climate, CO_2, and nitrogen deposition outweighed the effects of wildfire and insects, making Canada's forests a net carbon sink in the same period (Chen *et al*., 2003). In the United States, land use change and timber harvesting seem to be dominant factors according to repeated forest inventories from 1952 to 1997 that show forest carbon stocks (excluding soils) increasing by about 175 Mt C yr^{-1}. The most recent inventories show a decline in the rate of carbon uptake by forests, which appears to be mainly the result of changing growth and harvest rates following a long history of land-use change and management (Birdsey *et al*., 2006; Smith and Heath, 2005). The factors behind net emissions form Mexico's forests are deforestation, forest degradation, and forest fires that are not fully offset by forest regeneration (Masera *et al.*, 1997; de Jong *et al*., 2000).

Effects of Land-Use Change

Since 1990, approximately 549,000 ha of former cropland or grassland in Canada have been abandoned and are reverting to forest, while 71,000 ha of forest have been converted to cropland, grassland, or settlements, for a net increase in forest area of 478,000 ha (Environment Canada, 2005). In 2004, approximately 25,000 ha were converted from forest to cropland, 19,000 ha from forest to settlements and approximately 3,000 ha converted to wetlands. These land use changes resulted in emissions of about 4 Mt C (Environment Canada 2006).

In the last century more than 130 million hectares of land in the conterminous United States were either afforested (62 million ha) or deforested (70 million ha) (Birdsey and Lewis 2003). Houghton *et al*. (1999) estimated that cumulative changes in forest carbon stocks for the period from 1700 to 1990 in the United States were about +25 Gt C, primarily from conversion of forestland to agricultural use and reduction of carbon stocks for wood products.

Emissions from Mexican forests to the atmosphere are primarily due to the impacts of deforestation to pasture and degradation of 720,000 to 880,000 ha per year (Masera *et al*., 1997; Palacio *et al.* 2000). The highest deforestation rates occur in the tropical deciduous forests (304,000 ha in 1990) and the lowest in temperate broadleaf forests (59,000 ha in 1990).

Effects of Forest Management

The direct human impact on North American forests ranges from very minimal for protected areas to very intense for plantations (Table 11-4). Between these extremes is the vast majority of forestland, which is impacted by a wide range of human activities and government policies that influence harvesting, wood products, and regeneration.

Table 11-4. Area of forestland by management class and country, 2000 (1000 ha).

Forests and other wooded land in Canada occupy about 402 Mha. Approximately 310 Mha is considered forest of which 255 Mha (83%) are under active forest management (Environment Canada, 2006). Managed forests are considered to be under the direct influence of human activity and not reserved. Less than 1% of the area under active management is harvested annually. Apps *et al*. (1999) used a carbon budget model to simulate carbon in harvested wood products (HWP) for Canada. Approximately 800 Mt C were stored in the Canadian HWP sector in 1989, of which 50 Mt C were in imported wood products, 550 Mt C in exported products, and 200 Mt C in wood products produced and consumed domestically.

Between 1990 and 2000, about 4 Mha yr^{-1} were harvested in the U.S., two-thirds by partial-cut harvest and one-third by clear-cut (Birdsey and Lewis, 2003). Between 1987 and 1997, about 1 Mha yr^{-1} were planted with trees, and about 800,000 ha were treated to improve the quality and/or quantity of timber produced (Birdsey and Lewis, 2003). Harvesting in U.S. forests accounts for substantially more tree mortality than natural causes such as wildfire and insect outbreaks (Smith *et al*., 2004). The harvested wood resulted in -57 Mt C added to landfills and products in use, and an additional 88 Mt C were emitted from harvested wood burned for energy (Skog and Nicholson, 1998).

About 80% of the forested area in Mexico is socially owned by communal land grants (*ejidos*) and rural communities. About 95% of timber harvesting occurs in native temperate forests (SEMARNAP, 1996). Illegal harvesting involves 13.3 million m^3 of wood every year (Torres, 2004). The rural population is the controlling factor for changes in carbon stocks from wildfire, wood extraction, shifting agriculture practices, and conversion of land to crop and pasture use.

Effects of Climate and Atmospheric Chemistry

Environmental factors, including climate variability, nitrogen deposition, tropospheric ozone, and elevated CO_2, have been recognized as significant factors affecting the carbon cycle of forests (Aber *et al*., 2001; Ollinger *et al*., 2002). Some studies indicate that these effects are significantly smaller than the effects of land management and land-use change (Caspersen *et al*., 2000; Schimel *et al*., 2000). Recent reviews of ecosystem-scale studies known as Free Air CO_2 Exchange (FACE) experiments suggest that rising CO_2 increases net primary productivity by 12–23% over all species (Norby *et al*., 2005; Nowak *et al*., 2004). However, it is uncertain whether this effect results in a lasting increase in sequestered carbon or causes a more rapid cycling of carbon between the ecosystem and the atmosphere (Korner *et al*., 2005; Lichter, 2005). Experiments have also shown that the effects of rising CO_2 are significantly moderated by increasing tropospheric ozone (Karnosky *et al*., 2003; Loya *et al*., 2003). When nitrogen availability is also considered, reduced soil fertility limits the response to rising CO_2, but nitrogen deposition can increase soil fertility to counteract that effect (Finzi *et al.* 2006; Johnson *et al*., 1998; Oren *et al*., 2001). Observations of photosynthetic activity from satellites suggest that productivity changes due to lengthening of the growing season depend on whether areas were disturbed by fire (Goetz *et al*., 2005). Based on these conflicting and complicated results from different studies and approaches, a definitive assessment of the relative importance, and interactions, of natural and anthropogenic factors is a high priority for research (U.S. Climate Change Science Program, 2003).

Effects of Natural Disturbances

Wildfire, insects, diseases, and weather events are common natural disturbances in North America. These factors impact all forests but differ in magnitude by geographic region.

Wildfires were the largest disturbance in the twentieth century in Canada (Weber and Flannigan, 1997). In the 1980s and 1990s, the average total burned area was 2.6 Mha yr^{-1} in Canada's forests, with a maximum 7.6 Mha yr^{-1} in 1989. Carbon emissions from forest fires range from less than +1 Mt C yr^{-1} in the interior of British Columbia to more than +10 Mt C yr^{-1} in the western boreal forest. Total emissions from forest fires in Canada averaged approximately +27 Mt C yr^{-1} between 1959 and 1999 (Amiro *et al*., 2001). Estimated carbon emissions from four major insect pests in Canadian forests (spruce budworm, jack pine budworm, hemlock looper, and mountain pine beetle) varied from +5 to 10 Mt C yr^{-1} in the 1970s to less than +2 Mt C yr^{-1} in the mid-1990s[1]. Much of the Canadian forest is expected to experience increases in fire severity (Parisien *et al*., 2005) and burn areas (Flannigan *et al*., 2005), and continued outbreaks of forest pests are also likely (Volney and Hirsch, 2005).

In U.S. forests insects, diseases, and wildfire combined affect more than 30 Mha per decade (Birdsey and Lewis, 2003). Damage from weather events (hurricanes, tornados, ice storms) may exceed 20 Mha per decade (Dale *et al*., 2001). Although forest inventory data reveal the extent of tree mortality attributed to all causes combined, estimates of the impacts of individual categories of natural disturbance on carbon pools of temperate forests are scarce. The impacts of fire are clearly significant. According to one estimate, the average annual carbon emissions from biomass burning in the contemporary United States ranges from 9 to 59 Mt C (Leenhouts, 1998). McNulty (2002) estimated that large hurricanes in the United States could convert 20 Mt C of live biomass into detrital carbon pools.

The number and area of sites affected by forest fires in Mexico have fluctuated considerably between 1970 and 2002 with a clear tendency of an increasing number of fire events (4,000–7,000 in the 1970s and 1,800–15,000 in the 1990s), and overall, larger areas are being affected (0.08–0.25 Mha in 1970s and 0.05–0.85 Mha in 1990s). During El Nino years, increasing drought increases fire frequencies (Torres, 2004). Between 1995 and 2000, an average 8,900 fire events occurred per year and affected about 327,000 ha of the forested area. Currently, no estimates are available on the contribution of these fires to CO_2 emissions. Pests and diseases are important natural disturbance agents in temperate forests of Mexico; however, no statistics exist on the extent of the affected land area.

Projections of Future Trends

Large portions of the Canadian and Alaskan forest are expected to be particularly sensitive to climate change (Hogg and Bernier, 2005). Climate change effects on forest growth could be positive (e.g., increased rates of photosynthesis and increased water use efficiency) or negative (decreased water availability, higher rates of respiration) (Baldocchi and Amthor, 2001). It is difficult to predict the direction of these changes and they will likely vary by species and local conditions of soils and topography (Johnston and Williamson, 2005). Because of the large area of boreal forests and expected

[1]These estimates are the product of regional carbon density values, the proportion of mortality in defoliated stands given in Kurz and Apps (1999), data on area affected taken from NFDP (2005), and the proportion of C in insect-killed stands that is emitted directly to the atmosphere (0.1) from the disturbance matrix for insects used in the CBM-CFS (Kurz *et al*., 1992).

high degree of warming in northern latitudes, Canada and Alaska require close monitoring over the next few decades as these areas will likely be critical to determining the carbon balance of North America.

Assessments of future changes in carbon and vegetation distribution in the U.S. suggest that under most future climate conditions, NPP would respond positively to changing climate but total carbon storage would remain relatively constant (VEMAP Members, 1995; Pan *et al*., 1998; Neilson *et al*., 1998; Joyce *et al*., 2001). Under most climate scenarios the West gets wetter; when coupled with higher CO_2 and longer growing seasons, simulations show woody expansion and increased sequestration of carbon as well as increases in fire (Bachelet *et al*., 2001). However, recent scenarios from the Hadley climate model show drying in the Northwest, which produces some forest decline (Price *et al*., 2004). Many simulations show continued growth in eastern forests through the end of the twenty-first century, but some show the opposite, especially in the Southeast. Eastern forests could experience a period of enhanced growth in the early stages of warming, due to elevated CO_2, increased precipitation, and a longer growing season. However, further warming could bring on increasing drought stress, reducing the carrying capacity of the ecosystem and causing carbon losses through drought-induced dieback and increased fire and insect disturbances.

For Mexican forests, deforestation will continue to cause large carbon emissions in the years to come. However, government programs (since 2001) are trying to reduce deforestation rates and forest degradation, implement sustainable forestry in native forests, promote commercial plantations and diverse agroforestry systems, and promote afforestation and protection of natural areas (Masera *et al*., 1997).

OPTIONS FOR MANAGEMENT

Forest management strategies can be adapted to increase the amount of carbon uptake by forest systems. Alternative strategies for wood products are also important in several ways: how long carbon is retained in use, how much wood is used for biofuel, and substitution of wood for other materials that use more energy to produce. The net effect of these management and production strategies on carbon stocks and emissions will depend on emerging government policies for greenhouse gas management, the area of forests under management, management objectives for resources other than carbon, and the type of management and production regime being considered.

The forest sector includes a variety of activities that can contribute to increasing carbon sequestration, including: afforestation, mine land reclamation, forest restoration, agroforestry, forest management, biomass energy, forest preservation, wood products management, and urban forestry (Birdsey *et al*., 2000). Although the science of managing forests specifically for carbon sequestration is not well developed, some ecological principles are emerging to guide management decisions (Appendix 11.B). The prospective role of forestry in helping to stabilize atmospheric CO_2 depends on government policy, harvesting and disturbance rates, expectations of future forest productivity, the fate and longevity of forest products, and the ability to deploy technology and forest practices to increase the retention of sequestered CO_2. Market factors are also important in guiding the behavior of the private sector.

For Canada, Price *et al*. (1997) examined the effects of reducing natural disturbance, manipulating stand density, and changing rotation lengths for a forested landscape in northwest Alberta. By replacing natural disturbance (fire) with a simulated harvesting regime, they found that long-term equilibrium carbon storage increased from 105 to 130 Mt C. Controlling stand density following harvest had minimal impacts in the short term but increased landscape-level carbon storage by 13% after 150 years. Kurz *et al*. (1998) investigated the impacts on landscape-level carbon storage of the transition from natural to managed disturbance regimes. For a boreal landscape in northern Quebec, a simulated fire disturbance interval of 120 yr was replaced by a harvest cycle of 120 yr. The net impact was that the average age of forests in the landscape declined from 110 yr to 70 yr, and total carbon storage in forests declined from 16.3 to 14.8 Mt C (including both ecosystem and forest products pools).

Market approaches and incentive programs to manage greenhouse gases, particularly CO_2, are under development in the United States, the European Union, and elsewhere (Totten, 1999). Since forestry activities have highly variable costs because of site productivity and operational variability, most recent studies of forestry potential develop “cost curves”, i.e., estimates of how much carbon will be sequestered by a given activity for various carbon prices (value in a market system) or payments (in an incentive system). There is also a temporal dimension to the analyses because the rate of change in forest carbon stocks is variable over time, with forestry activities tending to have a high initial rate of net carbon sequestration followed by a lower or even a negative rate as forests reach advanced age.

In the United States, a bundle of forestry activities could potentially increase carbon sequestration from -100 to -200 Mt C yr^{-1} according to several studies (Birdsey *et al*., 2000; Lewandrowski, 2004; Environmental Protection Agency, 2005; Stavins and Richards, 2005). The rate of annual mitigation would likely decline over time as low-cost forestry opportunities become scarcer, forestry sinks become saturated, and timber harvesting takes place. Economic analyses of the U.S. forestry potential have focused on three broad categories of activities: afforestation (conversion of agricultural land to forest), improved management of existing forests, and use of woody biomass for fuel. Improved management of existing forest lands may be attractive to landowners at a carbon prices below $10 per ton of CO_2; afforestation requires a moderate price of $15 per ton of CO_2 or more to induce landowners to participate; and biofuels become dominant at prices of $30-50 per ton of CO_2 (Lewandrowski, 2004; Stavins and Richards, 2005; Environmental Protection Agency, 2005). Table 11-5 shows a simple scenario of emissions reduction below baseline, annualized over the time period 2010-2110, for forestry activities as part of a bundle of reduction options for the land base.

Table 11-5. Illustrative emissions reduction potential of various forestry activities in the United States under a range of prices and sequestration rates.

Production of renewable materials that have lower life-cycle emissions of greenhouse gases than non-renewable alternatives is a promising strategy for reducing emissions. Lippke *et al*. (2004) found that wood components used in residential construction had lower emissions of CO_2 from energy inputs than either concrete or steel.

Co-benefits are vitally important for inducing good forest carbon management. For example, conversion of agricultural land to forest will generally have positive effects on water, air, and soil quality and on biodiversity. In practice, some forest carbon sequestration projects have already been initiated even though sequestered carbon has little current value (Winrock International, 2005). In many of the current projects, carbon is a secondary objective that supports other landowner interests, such as restoration of degraded habitat. But co-effects may not all be beneficial. Water quantity may decline because of increased transpiration by trees relative to other vegetation. And taking land out of crop production may affect food prices—at higher carbon prices, nearly 40 million ha may be converted from cropland to forest (Environmental Protection Agency, 2005). Implementation of a forest carbon management policy will need to carefully consider co-effects, both positive and negative.

DATA GAPS AND INFORMATION NEEDS FOR DECISION SUPPORT

Decisions concerning carbon storage in North American forests and their management as carbon sources and sinks will be significantly improved by (1) filling gaps in inventories of carbon pools and fluxes, (2) a better understanding of how management practices affect carbon in forests, and (3) the increased availability of decision support tools for carbon management in forests.

Major Data Gaps in Estimates of Carbon Pools and Fluxes

Effective carbon policy and management to increase carbon sequestration and/or reduce emissions requires thorough understanding of current carbon stock sizes and flux rates, and responses to disturbance. Data gaps complicate analyses of the potential for policies to influence natural, social and economic drivers that can change carbon stocks and fluxes. Forests in an area as large as North America are quite diverse, and comprehensive data sets that can be used to analyze forestry opportunities, such as spatially explicit historical management and disturbance rates and effects on the carbon cycle, would enable managers to change forest carbon stocks and fluxes.

In the United States, the range of estimates of the size of the land carbon sink is between 0.30 and 0.58 Mt C yr^{-1} (Pacala *et al*., 2001). Significant data gaps among carbon pools include carbon in wood products, soils, woody debris, and water transport (Birdsey, 2004; Pacala *et al*., 2001). Geographic areas that are poorly represented in the available data sets include much of the Intermountain Western United States and Alaska, where forests of low productivity have not been inventoried as intensively as more productive timberlands (Birdsey, 2004). Accurate quantification of the relative magnitude of various causal mechanisms at large spatial scales is not yet possible, although research is ongoing to combine various approaches and data sets: large-scale observations, process-based modeling, ecosystem experiments, and laboratory investigations (Foley and Ramankutty, 2004).

Data gaps exist for Canada, particularly regarding changes in forest soil carbon and forestlands that are considered “unmanaged” (17% of forest lands). Aboveground biomass is better represented in forest inventories; however, the information needs to be updated and made more consistent among provinces. The new Canadian National Forest Inventory, currently under way, will provide a uniform coverage at a 20×20 km grid that will be the basis for future forest carbon inventories. Data are also lacking on carbon fluxes, particularly those due to insect outbreaks and forest stand senescence. The ability to model forest carbon stock changes has considerably improved with the release of the CBM (Kurz *et al*., 2002); however the CBM does not consider climate change impacts (Price *et al*., 1999; Hogg and Bernier, 2005).

For Mexico, there is very little data about measured carbon stocks for all forest types. Information on forest ecosystem carbon fluxes is primarily based on deforestation rates, while fundamental knowledge of carbon exchange processes in almost all forest ecosystems is missing. That information is essential for understanding the effects of both natural and human-induced drivers (hurricanes, fires, insect outbreaks, climate change, migration, and forest management strategies), which all strongly impact the forest carbon cycle. Current carbon estimates are derived from studies in preferred sites in natural reserves with species-rich tropical forests. Therefore, inferences made from the studies on regional and national carbon stocks and fluxes probably give biased estimates on the carbon cycle.

Major Data Gaps in Knowledge of Forest Management Effects

There is insufficient information available to guide land managers in specific situations to change forest management practices to increase carbon sequestration, and there is some uncertainty about the longevity of effects (Caldeira *et al*., 2004). This reflects a gap in the availability of inexpensive techniques for measuring, monitoring, and predicting changes in ecosystem carbon pools at the smaller scales appropriate for managers. There is more information available about management effects on live biomass and woody debris, and less about effects on soils and wood products. This imbalance in data has the potential to produce unintended consequences if predicted results are based on incomplete carbon accounting.

In the tropics, agroforestry systems offer a promising economic alternative to slash-and-burn agriculture, including highly effective soil conservation practices and mid-term and long-term carbon mitigation options (Soto-Pinto *et al*., 2001; Nelson and de Jong, 2003; Albrecht and Kandji, 2003). However, a detailed assessment of current implementations of agroforestry systems in different regions of Mexico is missing. Agroforestry also has potential in temperate agricultural landscapes, but as with forest management, there is a lack of data about how specific systems affect carbon storage (Nair and Nair, 2003).

Refining management of forests to realize significant carbon sequestration while at the same time continuing to satisfy the other needs and services of provided by forests (e.g., timber harvest, recreational value, watershed management) will require a multi-criteria decision support framework for a holistic and adaptive management program of the carbon cycle in North American forests. For example, methods should be developed for enhancing the efficiency of forest utilization as a renewable energy source, increasing the carbon storage per acre from existing forests, or even increasing the acreage devoted to forest systems that provide carbon sequestration. Currently there is little information about how appropriate incentives might be applied to accomplish these goals effectively, but given the importance of forests in the global carbon cycle, success in this endeavor could have important long-term and large-scale effects on global atmospheric carbon stocks.

Availability Of Decision-Support Tools

Few decision-support tools for land managers that include complete carbon accounting are available. Some are in development or have been used primarily in research studies (Proctor *et al*., 2005; Potter *et al*., 2003). As markets emerge for trading carbon credits, and if credits for forest management activities have value in those markets, then the demand for decision-support tools will encourage their development.

CHAPTER 11 REFERENCES

Aber, J., R.P. Neilson, S. McNulty, J.M. Lenihan, D. Bachelet, and R.J. Drapek, 2001: Forest processes and global change: predicting the effects of individual and multiple stressors. *BioScience* **51(9)**, 735–751.

Albrecht, A. and S.T. Kandji, 2003: Carbon sequestration in tropical agroforestry systems. *Agriculture, Ecosystems and Environments*, **99**, 15–27.

Amiro, B.D., J.B. Todd, B.M. Wotton, K.A. Logan, M.D. Flannigan, B.J. Stocks, J.A. Mason, D.L. Martell and K.G. Hirsch, 2001: Direct carbon emissions from Canadian forest fires, 1959-1999. *Canadian Journal of Forest Research*, **31**, 512–525.

Amiro, B.D., A.G. Barr, T.A. Black, H. Iwashita, N. Kljun, J.H. McCaughey, K. Morgenstern, S. Murayama, Z. Nesic, A.L. Orchansky, and N. Saigusa, 2005: Carbon, energy and water fluxes at mature and disturbed forest sites, Saskatchewan, Canada. *Agricultural and Forest Meteorology* (in press).

Apps, M.J., W.A. Kurz, S.J. Beukema, and J.S. Bhatti, 1999: Carbon budget of the Canadian forest product sector. *Environmental Science & Policy*, **2,** 25–41.

Arain, M.A. and N. Restrepo-Coupe, 2005: Net ecosystem production in an eastern white pine plantation in southern Canada. *Agricultural and Forest Meteorology*, **128**, 223–241.

Bachelet, D., R.P. Neilson, J.M. Lenihan, and R.J. Drapek, 2001: Climate change effects on vegetation distribution and carbon budget in the United States. *Ecosystems*, **4**, 164–185.

Baldocchi, D.D. and J.S. Amthor, 2001: Canopy photosynthesis: history, measurements and models. In: *Terrestrial Global Productivity* [Roy, J., B. Saugier, and H. Mooney (eds.)]. Academic Press, San Diego, USA, pp. 9–31.

Barford C.C., S.C. Wofsy, M.L. Goulden, J.W. Munger, E.H. Pyle, S.P. Urbanski, L. Hutyra, S.R. Saleska, D. Fitzjarrald, and K. Moore, 2001: Factors controlling long- and short-term sequestration of atmospheric CO_2 in a mid-latitude forest. *Science*, **294**, 1688–1691.

Bechtold, W.A. and P.L. Patterson (eds.), 2005: *The Enhanced Forest Inventory and Analysis Program – National Sampling Design and Estimation Procedures*. General Technical Report SRS-80, U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC, 85 pp.

Birdsey, R.A. and L.S. Heath, 1995: Carbon changes in U.S. forests. In: *Climate Change and the Productivity Of America's Forests* [Joyce, L.A. (ed.)]. U. S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station General Technical Report, Fort Collins, CO, pp. 56–70.

Birdsey, R.A., R. Alig, and D. Adams, 2000: Migitation activities in the forest sector to reduce emissions and enhance sinks of greenhouse gases. In: *The Impact of Climate Change on America's Forests: A Technical Document Supporting the 2000 USDA Forest Service RPA Assessment* [Joyce, L.A. and R.A. Birdsey (eds.]). RMRS-GTR-59, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, pp. 112–131.

Birdsey, R.A., 2004: Data gaps for monitoring forest carbon in the United States: an inventory perspective. In: [Mickler, R.A. (ed.)]. *Environmental Management*, **33(Suppl. 1)**, S1-S8.

Birdsey, R.A. and G.M. Lewis, 2003: Current and historical trends in use, management, and disturbance of U.S. forestlands. In: *The Potential of U.S. Forest Soils to Sequester Carbon and Mitigate the Greenhouse Effect* [Kimble, J.M., L.S. Heath, and R.A. Birdsey (eds.)]. CRC Press LLC, New York, NY, pp. 15–33.

Birdsey, R., K. Pregitzer, and A. Lucier, 2006: Forest carbon management in the United States, 1600-2100. *Journal of Environmental Quality* (in press).

Caldeira, K., M.G. Morgan, D. Baldocchi, P.G. Brewer, C.-T.A. Chen, G.-J. Nabuurs, N. Nakicenovic, and G.P. Robertson, 2004: A portfolio of carbon management options. In: *The Global Carbon Cycle* [Field, C.B. and M.R. Raupach (eds.)]. Island Press. Washington, DC.

Caspersen, J.P., S.W. Pacala, J.C. Jenkins, G.C. Hurtt, P.R. Moorcraft, and R.A. Birdsey, 2000: Contributions of land-use history to carbon accumulation in U.S. forests. *Science*, **290**, 1148–1151.

CFS (Canadian Forest Service), 2005: *State of the Forest Report, 2004-2005*. Canadian Forest Service, Natural Resources Canada, Ottawa, Ontario, Canada. Available at http://www.nrcan-rncan.gc.ca/cfs-scf/national/what-quoi/sof/latest_e.html

Chapin, F.I., G. Woodwell, J. Randerson, G. Lovett, E. Rastetter, D. Baldocchi, D. Clark, M. Harmon, D. Schimel, R. Valentini, C. Wirth, J. Aber, *et al*.: Reconciling carbon cycle terminology: a search for consensus. *Ecosystems* (in review).

Chen, J.M., W. Ju, and J. Cihlar, *et al*., 2003: Spatial distribution of carbon sources and sinks in Canada's forests. *Tellus B*, 1–20.

Clark, K.L., H.L. Gholz, and M.S. Castro, 2004: Carbon dynamics along a chronosequence of slash pine plantations in north Florida. *Ecological Applications*, **14**, 1154–1171.

Dale, V.H., L.A. Joyce, S. McNulty, R.P. Neilson, *et al*., 2001: Climate change and forest disturbances. *Bioscience*, **51(9)**, 723–734.

De Jong, B.H.J., S. Ochoa-Gaona, M.A. Castillo-Santiago, N. Ramirez-Marcial, and M.A. Cairns, 2000: Carbon fluxes and patterns of land-use/land-cover change in the Selva Lacandona, Mexico. *Ambio*, **29**, 504–511.

Environment Canada, 2005: *Canada's Greenhouse Gas Inventory 1990–2004: Initial Submission*. Greenhouse Gas Division, Environment Canada, Ottawa, Ontario, Canada. Available at http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/2761.php

Environmental Protection Agency, 2005: *Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture*. U.S. Environmental Protection Agency, Washington, DC, 154 pp.

Finzi, A.C., D.J.P. Moore, E.H. DeLucia, J. Lichter, K.S. Hofmockel, R.P. Jackson, H.-S. Kim, R. Matamala, H.R. McCarthy, R. Oren, J.S. Pippen, and W.H. Schlesinger, 2006: Progressive nitrogen limitation of ecosystem processes under elevated CO_2 in a warm-temperate forest. *Ecology* **87**(1): 15-25.

Fitzsimmons, M.J., D.J. Pennock, and J. Thorpe, 2004: Effects of deforestation on ecosystem carbon densities in central Saskatchewan, Canada. *Forest Ecology and Management*, **188**, 349–361.

Flannigan, M.D., K.A. Logan, B.D. Amiro, W.R. Skinner, and B.J. Stocks, 2005: Future area burned in Canada. *Climatic Change*, **72**, 1–16.

Foley, J.A. and N. Ramankutty. A primer on the terrestrial carbon cycle: what we don't know but should. In: *The Global Carbon Cycle* [Field, C.B. and M.R. Raupach (eds.)]. Island Press, Washington, DC.

Food and Agriculture Organization, 2001: *Global Forest Resources Assessment 2000. Main Report*. FAO Forestry Paper 140, Rome, Italy, 481 pp.

Giardina, C.P., D. Binkley, M.G. Ryan, J.H. Fownes, R.S. Senock, 2004: Belowground carbon cycling in a humid tropical forest decreases with fertilization. *Oecologia*, **139**, 545–550.

Goetz, S.J., A.G. Bunn, G.J. Fiske, and R.A. Houghton, 2005: Satellite-observed photosynthetic trends across boreal North America associated with climate and fire disturbance. *PNAS* **102**(**38**): 13521-13525.

Goodale, C.L., M.J. Apps, R.A. Birdsey, C.B. Field, L.S. Heath, R.A. Houghton, J.C. Jenkins, G.H. Kohlmaier, W. Kurz, S. Liu, G.-J. Nabuurs, S. Nilsson, and A.Z. Shvidenko, 2002: Forest carbon sinks in the northern hemisphere. *Ecological Applications*, **12**, 891–899.

Griffis, T.J., T.A. Black, K. Morgenstern, A.G. Barr, Z. Nesic, G.B. Drewitt, D. Gaumont-Guay, and J.H. McCaughey, 2003: Ecophysiological controls on the carbon balances of three southern boreal forests. *Agricultural and Forest Meteorology*, **117**(**1–2**), 53–71.

Harmon, M.E., J.M. Harmon, W.K. Ferrell, and D. Brooks, 1996: Modeling carbon stores in Oregon and Washington forest products: 1900-1992. *Climatic Change*, **33**, 521–550.

Harmon, M., 2001: Carbon sequestration in forests - addressing the scale question. *Journal of Forestry*, **99**, 24–29.

Harmon, M. and P. Marks, 2002: Effects of silvicultural practices on carbon stores in Douglas-fir-western hemlock forests in the Pacific Northwest, USA: results from a simulation model. *Canadian Journal of Forest Research*, **32(5)**, 863–877.

Haynes, R.W. (ed.), 2003: *An Analysis of the Timber Situation in the United States: 1952-2050*. General Technical Report PNW-GTR-560, USDA Forest Service, Portland, OR, 254 pp.

Heath, L.S. and J.E. Smith, 2004: Criterion 5, indicator 26: total forest ecosystem biomass and carbon pool, and if appropriate, by forest type, age class and successional change. In: *Data Report: A Supplement to the National Report on Sustainable Forests—2003* [Darr, D.R. (coord.)]. FS-766A, U.S. Department of Agriculture, Washington, DC, 14 pp. Available at http://www.fs.fed.us/research/sustain/contents.htm (8 June).

Heath, L.S. and J. E. Smith, 2000: An assessment of uncertainty in forest carbon budget projections. *Environmental Science & Policy*, **3**, 73–82.

Hogg, E.H. and P.Y. Bernier, 2005: Climate change impacts on drought-prone forests in western Canada. *Forestry Chronicle* (in press).

Houghton, R.A., J.L. Hackler, and K.T. Lawrence, 1999: The U.S. carbon budget: contributions from land-use change, *Science*, **285**, 574–578.

Humphreys, E.R., T.A. Black, K. Morgenstern, Z. Li, and Z. Nesic, 2005: Net ecosystem production of a Douglas-fir stand for three years following clearcut harvesting. *Global Change Biology*, **11**, 450–464.

Janisch, J. and M. Harmon, 2002: Successional changes in live and dead wood carbon stores: implications for net ecosystem productivity. *Tree Physiology*, **22**, 77–89.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey, 2003: National-scale biomass estimators for United States tree species. *Forest Science*, **49(1)**, 12–35.

Johnson, D.W., R.B. Thomas, K.L. Griffen, and D.T. Tissue, *et al*., 1998: Effects of carbon dioxide and nitrogen on growth and nitrogen uptake in ponderosa and loblolly pine. *Journal of Environmental Quality*, **27**, 414–425.

Johnston, M. and T. Williamson, 2005: Climate change implications for stand yields and soil expectation values: a northern Saskatchewan case study. *Forestry Chronicle*, **81**, 683–690.

Joyce, L., J. Baer, S. McNulty, V. Dale, A. Hansen, L. Irland, R. Neilson, and K. Skog, 2001: Potential consequences of climate variability and change for the forests of the United States: In: *Climate Change Impacts in the United States*. Report for the U.S Global Change Research Program. Cambridge University Press, Cambridge, United Kingdom, pp. 489-521.

Karnosky, D.F., D.R. Zak, K.S. Pregitzer, C.S. Awmack, *et al*., 2003: Tropospheric ozone moderates responses of temperate hardwood forests to elevated CO_2: a synthesis of molecular to ecosystem results from the Aspen FACE project. *Functional Ecology*, **17**, 289–304.

Korner, C., 2000: Biosphere responses to CO_2 enrichment. *Ecological Applications*, **10**, 1590–1619.

Korner, C., R. Asshof, O. Bignucolo, and S. Haattenschwiler, *et al*., 2005. Carbon flux and growth in mature decidous forest trees exposed to elevated CO_2. *Science*, **309**, 1360–1362.

Kurz, W.A., M.J. Apps, T.M. Webb, and P.J. McNamee, 1992: *The Carbon Budget of the Canadian Forest Sector: Phase 1*. Information Report NOR-X-326, Forestry Canada, Northern Forestry Centre, Edmonton, Alberta, Canada.

Kurz, W.A., S. Beukema, and M.J. Apps: 1998: Carbon budget implications of the transition from natural to managed disturbance regimes in forest landscapes. *Mitigation and Adaptation Strategies for Global Change*, **2**, 405–421.

Kurz, W.A. and M.J. Apps, 1999: A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. *Ecological Applications,* **9**, 526–547.

Kurz, W., M. Apps, E. Banfield, and G. Stinson, 2002: Forest carbon accounting at the operational scale. *The Forestry Chronicle*, **78**, 672–679.

Law, B.E., E. Falge, D.D. Baldocchi, P. Bakwin, P. Berbigier, K. Davis, A.J. Dolman, M. Falk, J.D. Fuentes, A. Goldstein, A. Granier, A. Grelle, D. Hollinger, I.A. Janssens, P. Jarvis, N.O. Jensen, G. Katul, Y. Mahli, G. Matteucci, R. Monson, W. Munger, W. Oechel, R. Olson, K. Pilegaard, K.T. Paw U, H. Thorgeirsson, R. Valentini, S. Verma, T. Vesala, K. Wilson, and S. Wofsy, 2002: Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation*. Agricultural and Forest Meteorology,* **113**, 97–120.

Leenhouts, B., 1998: Assessment of biomass burning in the conterminous United States. *Conservation Ecology*, **2(1)**, 1.

Lewandrowski, J., M. Sperow, M. Peters, M. Eve, C. Jones, K. Paustian, and R. House, 2004: *Economics of Sequestering Carbon in the U.S. Agricultural Sector*. Technical Bulletin 1909, U.S. Department of Agriculture, Economic Research Service, Washington, DC, 61 pp.

Lichter, J., S.H. Barron, C.E. Bevacqua, A.C. Finzi, K.F. Irvine, *et al*., 2005: Soil carbon sequestration and turnover in a pine forest after six years of atmospheric CO_2 enrichment. *Ecology*, **86(7)**, 1835–1847.

Lippke, B., J. Wilson, J. Perez-Garcia, J. Bowyer, and J. Miel, 2004: CORRIM: Life cycle environmental performance of renewable building materials. *Forest Products Journal* **54**(**6**): 8-19.

Loya, W.M., K.S. Pregitzer, N.J. Karberg, J.S. King, and C.P. Giardina, 2003: Reduction of soil carbon formation by tropospheric ozone under increased carbon dioxide levels. *Nature*, **425**, 705–707.

Lugo, A.E., J.F. Colón, and F.N. Scatena, 1999: The Caribbean. In: *North American Terrestrial Vegetation* [Barbour, M.G. and W.D. Billings (eds.)]. Cambridge University Press, Cambridge, United Kingdom, 530 pp.

Masera, O., M.J. Ordóñez, and R. Dirzo, 1997a: Carbon emissions from Mexican forests: the current situation and long-term scenarios. *Climatic Change,* **35**, 265–295.

Masera, O., A. Delia Cerón, and A. Ordóñez, 2001: Forestry mitigation options for Mexico: finding synergies between national sustainable development priorities and global concerns. *Mitigation and Adaptation Strategies for Global Change*, **6**, 291–312.

McNulty, S.G., 2002: Hurricane impacts on U.S. forest carbon sequestration. *Environmental Pollution*, **116**, S17–S24.

Nair, P.K.R, and V.D. Nair, 2003: Carbon storage in North American agroforestry systems. In: J.Kimble, L.S. Heath, R.A. Birdsey, and R. Lal (Eds.). The Potential of U.S. Forest Soils to Sequester Carbon and Mitigate the Greenhouse Gas Effect. CRC Press, Boca Raton, FL, pp. 333-346.

Natural Resources Canada, 2005: *The State of Canada's Forests*. Canadian Forest Service, Natural Resources Canada, Ottawa, Ontario, Canada. Available at http://www.nrcan-rncan.gc.ca/cfs-scf/national/what-quoi/sof/latest_e.html

Neilson, R.P., I.C. Prentice, and B. Smith, T.G.F. Kittel, and D. Viner, 1998: Simulated changes in vegetation distribution under global warming. In: *The Regional Impacts of Climate Change: An Assessment of Vulnerability* [Watson, R.T., M.C. Zinyowera, R.H. Moss, and D.J. Dokken (eds.)]. Cambridge University Press, Cambridge, United Kingdom, pp. 439-456.

Nelson, K.C. and B.H.J. de Jong, 2003: Making global initiatives local realities: carbon mitigation projects in Chiapas, Mexico. *Global Environmental Change*, **13**, 19-30.

NFDP (National Forestry Database Program), 2005: *Compendium of Canadian Forestry Statistics*. National Forestry Database Program, Canadian Council of Forest Ministers, Ottawa, Ontario, Canada. Available at http://nfdp.ccfm.org/compendium/index_e.php

Norby, R.J., E.H. DeLucia, and B. Gielen, *et al*., 2005: Forest response to elevated CO_2 is conserved across a broad range of productivity. *Proceedings of the National Academy of Sciences of the United States of America*, **102(50)**, 18052–18056.

Nowak, R.S., D.S. Ellsworth, and S.D. Smith, 2004: Functional responses of plants to elevated atmospheric CO_2- do photosynthetic and productivity data from FACE experiments support early predictions? *New Phytologist*, **162(2)**, 253.

Ollinger S.V, J.D. Aber, P.B. Reich, and R.J. Freuder, 2002: Interactive effects of nitrogen deposition, tropospheric ozone, elevated CO_2 land use history on the carbon dynamics of northern hardwood forests. *Global Change Biology*, **8**, 545–562.

Oren, R., D.S. Ellworth, K.S. Johnsen, and N. Phillips, *et al*., 2001: Soil fertility limits carbon sequestration by forest ecosystems in a CO_2-enriched atmosphere. *Nature*, **411**, 469–472.

Osher L.J., P.A. Matson, and R. Amundson, 2003: Effect of land use change on soil carbon in Hawaii. *Biogeochemistry*, **65(2)**, 213-232.

Pacala, S.W., G.C. Hurtt, D. Baker, P. Peylin, R.A. Houghton, R.A. Birdsey, L. Heath, E.T. Sundquist, and R.F. Stallard, *et al*., 2001: Consistent land and atmosphere-based U.S. carbon sink estimates. *Science*, **292**, 2316–2320.

Palacio, J.L., *et al*., 2000: *La condición actual de los recursos forestales en México: resultados del Inventario Forestal Nacional 2000*. Technical Note. *Investigaciones Geográficas*, **43**, 183–203.

Pan, Y., *et al*., 1998: Modeled responses of terrestrial ecosystems to elevated atmospheric CO_2: a comparison of simulations by the biogeochemistry models of the Vegetation/Ecosystem Modeling and Analysis Project (VEMAP). *Oecologia*, **114**, 389–404.

Parisien, M.-A., V. Kafka, N. Flynn, K.G. Hirsch, J.B. Todd, and M.D. Flannigan, 2005: *Fire Behavior Potential in Central Saskatchewan Under Predicted Climate Change*. PARC Summary Document 05-01, PARC (Prairie Adaptation Research Collaborative), Regina, Saskatchewan, 12 pp.

Peterson, E.B., G.M. Bonnor, G.C. Robinson, and N.M. Peterson, 1999: *Carbon Sequestration Aspects of an Afforestation Program in Canada's Prairie Provinces*. Submitted to Joint Forest Sector Table/Sinks Table, National Climate Change Process, Ottawa, Ontario, Canada. Available at http://www.nccp.ca/NCCP/national_process/issues/sinks_e.html

Potter, C., S.A. Klooster, R. Myneni, V. Genovese, P. Tan, and V. Kumar, 2003: Continental scale comparisons of terrestrial carbon sinks estimated from satellite data and ecosystem modeling 1982-98. *Global and Planetary Change*, **39**, 201–213.

Pregitzer, K.S. and E.S. Euskirchen, 2004: Carbon cycling and storage in world forests: biomes patterns related to forest age. *Global Change Biology*, **10**, 2052–2077.

Price, D.T., D.H. Halliwell, M.J. Apps, W.A. Kurz, and S.R. Curry, 1997: Comprehensive assessment of carbon stocks and fluxes in a Boreal-Cordilleran forest management unit. *Canadian Journal of Forest Research*, **27**, 2005–2016.

Price, D.T., D.W. McKenney, P. Papadopol, T. Logan, and M.F. Hutchinson, 2004: *High Resolution Future Scenario Climate Data for North America*. Proceedings of American Meteorological Society 26th Conference on Agricultural and Forest Meteorology, Vancouver, British Columbia, Canada, 23-26 August 2004, 13 pp.

Price, D.T., C.H. Peng, M.J. Apps, and D.H. Halliwell, 1999: Simulating effects of climate change on boreal ecosystem carbon pools in central Canada. *Journal of Biogeography*, **26**, 1237–1248.

Proctor, P., L.S. Heath, P.C. Van Deusen, J.H. Gove, and J.E. Smith, 2005: COLE: a web-based tool for interfacing with forest inventory data. In: *Proceedings of the Fourth Annual Forest Inventory and Analysis Symposium* [McRoberts, R.E., *et al*. (eds.)]. GTR-NC-252, USDA Forest Service.

Ryan, M.G., D. Binkley, and J.H. Fownes, 1997: Age-related decline in forest productivity: pattern and process. *Advances in Ecological Research*, **27**, 213–262.

Schimel, D., J. Melillo, H. Tian, A.D. McGuire, D. Kicklighter, T. Kittel, N. Rosenbloom, S. Running, P. Thornton, D. Ojima, W. Parton, R. Kelly, M. Sykes, R. Neilson, and B. Rizzo, 2000: Contribution of increasing CO_2 and climate to carbon storage by ecosystems in the United States. *Science*, **287**, 2004–2006.

Schoene, D. and M. Netto, 2005: The Kyoto Protocol: what does it mean for forests and forestry? *Unasylva* **222**(**56**): 3-11.

Schulze, E., J. Lloyd, F. Kelliher, C. Wirth, C. Rebmann, B. Luhker, M. Mund, A. Knohl, I. Milyukova, W. Schulze, W. Ziegler, A. Varlagin, A. Sogachev, R. Valentini, S. Dore, S. Grigoriev, O. Kolle, M. Panfyorov, N. Tchebakova, and N. Vygodskaya, 1999: Productivity of forests in the Eurosiberian boreal region and their potential to act as a carbon sink - a synthesis. *Global Change Biology*, **5**, 703–722.

Secretaría de Medio Ambiente, Recursos Naturales y Pesca (SEMARNAP), 1996: *Programa Forestal y de Suelo 1995–2000*. Poder ejecutivo Federal, SEMARNAP, México City.

Skog, K.E. and G.A. Nicholson, 1998: Carbon cycling through wood products: the role of wood and paper products in carbon sequestration. *Forest Products Journal*, **48**, 75–83. Available at (http://www.fpl.fs.fed.us/documnts/pdf1998/skog98a.pdf)

Smith, W.B., P.D. Miles, J.S. Vissage, and S.A. Pugh, 2004: *Forest Resources of the United States, 2002*. General Technical Report NC-241, USDA Forest Service, North Central Research Station, St. Paul, MN.

Smith, J.E. and L.S. Heath, 2005: Land use change and forestry and related sections. In: *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2003*. Excerpted, EPA 430-R-05-003, U.S. Environmental Protection Agency. Available at http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2005.html (18 August). [Note that some EPA contractors or employees may have written or edited some text, or formatted tables or redrew some figures for final EPA format.]

Smith, J.E. and L.S. Heath, 2000: Considerations for interpreting probabilistic estimates of uncertainty of forest carbon. In: *The Impact of Climate Change on America's Forests* [Joyce, L.A. and R. Birdsey (eds.)]. General Technical Report RMRS-GTR-59, USDA Forest Service, pp. 102–111.

Soto-Pinto, L., G. Jimenez-Ferrer, A.V. Guillen, B. de Jong Bergsma, E. Esquivel-Bazan, 2001: Experiencia agroforestral para la captura de carbono en comunidades indigenas de Mexico. *Revista Forestal Iberoamericana*, **1**, 44–50

Stainback, G.A. and J.R.R. Alavalapati, 2005: Effects of carbon markets on the optimal management of slash pine (Pinus elliottii) plantations. *Southern Journal of Applied Forestry*, **29(1)**, 27–32.

Stanturf, J.A., R.C. Kellison, F.S. Broerman, and S.B. Jones, 2003: Productivity of southern pine plantations – where we are and how did we get here? *Journal of Forestry*, 26–31, April/May 2003.

Stavins, R.N. and K.R. Richards, 2005: *The Cost of U.S. Forest-Based Carbon Sequestration*. The Pew Center on Global Climate Change, Arlington, VA, 40 pp. Available at www.pewclimate.org

Torres, R.J.M., 2004: *Estudio de tendencias y perspectivas del sector forestal en América Latina al año 2020*. Informe Nacional México, FAO. Available at http://www.fao.org/documents/show_cdr.asp?url_file=/docrep/006/j2215s/j2215s11.htm

Totten, M., 1999: *Getting it Right: Emerging Markets for Storing Carbon in Forests*. World Resources Institute, Washington, DC, 49 pp.

US Climate Change Science Program, 2003: *Strategic Plan for the Climate Change Science Program*. Washington, DC. Available at http://www.climatescience.gov/Library/stratplan2003/default.htm

VEMAP Members, 1995: Vegetation/ecosystem modeling and analysis project: comparing biogeography and biogeochemistry models in a continental-scale study of terrestrial ecosystem responses to climate change and CO_2 doubling. *Global Biogeochemical Cycles*, **9**, 407–437.

Volney, J.A.W. and K. Hirsch, 2005: Disturbing forest disturbances. *Forestry Chronicle*, **81**, 662–668.

Weber, M.G. and M.D. Flannigan, 1997: Canadian boreal forest ecosystem structure and function in a changing climate: impact on fire regimes. *Environmental Reviews*, **5**, 145–166.

Winrock International, 2005: *Ecosystem Services*. Date accessed unknown. Available at http://www.winrock.org/what/projects.cfm?BU=9086

Woodwell, G. and R. Whittaker, 1968: Primary production in terrestrial communities. *American Zoologist*, **8**, 19–30.

Table 11-1. Area of forest land by biome and country, 2000 (1000 ha)[1]

Ecological zone:	Canada[2]	U.S.[3]	Mexico[4]	Total
Tropical/subtropical	0	115,200	30,700	145,900
Temperate	101,100	142,400	32,900	276,400
Boreal	303,000	45,500	0	348,500
Total	404,100	303,100	63,600	770,800

[1]There is 95% certainty that the actual values are within 10% of those reported in this table (e.g., for the United States see Bechtold and Patterson, 2005).
[2]Canadian Forest Service, 2005
[3]Smith *et al*., 2004
[4]Palacio *et al*., 2000

Table 11-2. Carbon stocks in forests by ecosystem carbon pool and country (Mt C)[1]

Ecosystem carbon pool:	Canada[2]	U.S.[3]	Mexico[4]	Total
Biomass	14,500	24,900	7,700	47,100
Dead organic matter[5]	71,300	41,700	11,400	124,400
Total	85,800	66,600	19,100	171,500

[1]There is 95% certainty that the actual values are within 25% of those reported in this table (Heath and Smith, 2000; Smith and Heath, 2000).
[2]Kurz and Apps, 1999
[3]Heath and Smith, 2004; Birdsey and Heath, 1995
[4]Masera *et al*., 2001
[5]Includes litter, coarse woody debris, and soil carbon

Table 11-3. Change in carbon stocks for forests and wood products by country (Mt C yr^{-1})

Carbon pool:	Canada[1]	U.S.[2]	Mexico[3]	Total
Forest Ecosystem	–17	–236	+52	–201
Wood Products	–11	–57	ND[4]	–68
Total	–28	–293	+52	–269

[1]Data for 1990-2004, taken from Environment Canada (2006), Goodale *et al*. (2002). There is 95% certainty that the actual values are within 100% of those reported for Canada.
[2]From Smith and Heath, 2005 (excluding soils), and Pacala *et al*., 2001 (soils). Estimates do not include urban forests. There is 95% certainty that the actual values are within 50% of those reported for the United States.
[3]From Masera, 1997. There is 95% certainty that the actual values are within 100% of those reported for Mexico.
[4]Estimates are not available.

Table 11-4. Area of forestland by management class and country, 2000 (1000 ha)[1]

Management class:	Canada	U.S.	Mexico	Total
Protected	19,300	66,700	6,000	92,000
Plantation	4,500	16,200	200	20,900
Other	380,300	220,200	57,400	657,900
Total	404,100	303,100	63,600	770,800

[1]From Food and Agriculture Organization 2001; Natural Resources Canada 2005. Estimates in this table are within 10% of the true value at the 95% confidence level (e.g. for the U.S. see Bechtold and Patterson 2005).

Table 11-5. Illustrative emissions reduction potential of various forestry activities in the United States under a range of prices and sequestration rates[1]

Forestry activity	Carbon sequestration rate (t CO_2 ha^{-1} yr^{-1})	Price range ($/t CO_2)	Emissions reduction potential (Mt CO_2 yr^{-1})
Afforestation	5.4–23.5	15–30	137–823
Forest management	5.2–7.7	1–30	25–314
Biofuels	11.8–13.6	30–50	375–561

[1]Adapted from Environmental Protection Agency (2005). Maximum price analyzed was $50/t CO_2.

APPENDIX 11A
ECOSYSTEM CARBON FLUXES

The recent history of disturbance largely determines whether a forest system will be a net source or sink of C. For example, net ecosystem productivity (NEP, gains due to biomass growth minus losses due to respiration in vegetation and soil) is being measured across a range of forest types in Canada using the eddy covariance technique. In mature forests, values range from –19.6 t C ha^{-1} yr^{-1} in a white pine plantation in southern Ontario (Arain and Restrepo-Coupe, 2005) to –3.2 t C ha^{-1} yr^{-1} in a jack pine forest in (Amiro *et al*., 2005; Griffis *et al*., 2003). In recently disturbed forests, NEP ranges from +58.0 t C ha^{-1} yr^{-1} in a harvested Douglas-fir forest (Humphreys *et al*., 2005) to +5.7 t C ha^{-1} yr^{-1} in a 7 year old harvested jack pine forest (Amiro *et al*., 2005). In general, forest stands recovering from disturbance are sources of carbon until uptake from growth becomes greater than losses due to respiration, usually within 10 years (Amiro *et al*., 2005).

In the United States, extensive land-based measurements of forest/atmosphere carbon exchange reveal patterns and causes of sink or source strength (Table 11A-1). Results show that net ecosystem exchange (NEE) of carbon in temperate forests ranges from a source of +12.7 t C ha^{-1} yr^{-1} to a sink of –5.9 t C ha^{-1} yr^{-1}. Forests identified as sources are primarily forests in the earliest stages of regeneration (up to about 8 years) following stand-replacing disturbances such as wildfire and logging (Law *et al*., 2002). Mature temperate deciduous broadleaf forests and mature evergreen coniferous forests were an average sink of –2.7 and –2.5 t C ha^{-1} yr^{-1}, respectively (12 sites, 54 site-years of data). Values ranged from a source of +0.3 for a mixed deciduous and evergreen forest to a sink of –5.8 for an aggrading deciduous forest, averaged over multiple years. Young temperate evergreen coniferous forests (8 to 20 years) ranged from a sink of –0.6 to –5.9 t C ha^{-1} yr^{-1} (mean 3.1). These forests are still rapidly growing and have not reached the capacity for carbon uptake.

Mature forests can have substantial stocks of sequestered carbon. Disturbances that damage or replace forests can result in the land being a net source of carbon dioxide for a few years in mild climates to 10–20 years in harsh climates while the forests are recovering (Law *et al*., 2004; Clark *et al*., 2004). Thus, the range of observed annual NEE of carbon dioxide ranges from a source of about +13 t C ha^{-1} yr^{-1} in a clearcut forest to a net sink of –6 t C ha^{-1} in mature temperate forests.

For Mexican forests, estimates of net ecosystem carbon exchange are unavailable, but estimates from other tropical forests may indicate rates for similar systems in Mexico. In Puerto Rico, aboveground NPP in tropical forests range from –9.2 to –11.0 t C ha^{-1} yr^{-1} (Lugo *et al*., 1999). Belowground NPP measurements exist for only one site with –19.5 t C ha^{-1} yr^{-1} (Lugo *et al*., 1999). In Hawaii, aboveground and belowground NPP of native forests dominated by *Metreosideros polymorpha* vary depending on substrate age and precipitation regime. Aboveground NPP ranges between –4.0 to –14.0 t C ha^{-1} yr^{-1}, while belowground NPP ranges between –5.2 and –9.0 t C ha^{-1} yr^{-1} (Giardina *et al*., 2004). Soil carbon emissions along the substrate age gradient range from +2.2 to +3.3 t C ha^{-1} yr^{-1}, and along the precipitation gradient from +4.0 to +9.7 t C ha^{-1} yr^{-1} (Osher *et al*., 2003). NEP estimates are not available for these tropical forests, so their net impact on atmospheric carbon stocks cannot be calculated.

APPENDIX 11A REFERENCES

Amiro, B.D., A.G. Barr, T.A. Black, H. Iwashita, N. Kljun, J.H. McCaughey, K. Morgenstern, S. Murayama, Z. Nesic, A.L. Orchansky, and N. Saigusa, 2005: Carbon, energy and water fluxes at mature and disturbed forest sites, Saskatchewan, Canada. *Agricultural and Forest Meteorology* (in press).

Arain, M.A. and N. Restrepo-Coupe, 2005: Net ecosystem production in an eastern white pine plantation in southern Canada. *Agricultural and Forest Meteorology*, **128**, 223–241.

Clark, K.L., H.L. Gholz, and M.S. Castro, 2004: Carbon dynamics along a chronosequence of slash pine plantations in north Florida. *Ecological Applications*, **14**, 1154–1171.

Giardina, C.P., D. Binkley, M.G. Ryan, J.H. Fownes, R.S. Senock, 2004: Belowground carbon cycling in a humid tropical forest decreases with fertilization. *Oecologia*, **139**, 545–550.

Griffis, T.J., T.A. Black, K. Morgenstern, A.G. Barr, Z. Nesic, G.B. Drewitt, D. Gaumont-Guay, and J.H. McCaughey, 2003: Ecophysiological controls on the carbon balances of three southern boreal forests. *Agricultural and Forest Meteorology*, **117**(**1–2**), 53–71.

Humphreys, E.R., T.A. Black, K. Morgenstern, Z. Li, and Z. Nesic, 2005: Net ecosystem production of a Douglas-fir stand for three years following clearcut harvesting. *Global Change Biology*, **11**, 450–464.

Law, B.E., E. Falge, D.D. Baldocchi, P. Bakwin, P. Berbigier, K. Davis, A.J. Dolman, M. Falk, J.D. Fuentes, A. Goldstein, A. Granier, A. Grelle, D. Hollinger, I.A. Janssens, P. Jarvis, N.O. Jensen, G. Katul, Y. Mahli, G. Matteucci, R. Monson, W. Munger, W. Oechel, R. Olson, K. Pilegaard, K.T. Paw U, H. Thorgeirsson, R. Valentini, S. Verma, T. Vesala, K. Wilson, and S. Wofsy, 2002: Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation. *Agricultural and Forest Meteorology*, **113**, 97–120.

Lugo, A.E., J.F. Colón, and F.N. Scatena, 1999: The Caribbean. In: *North American Terrestrial Vegetation* [Barbour, M.G. and W.D. Billings (eds.)]. Cambridge University Press, Cambridge, United Kingdom, 530 pp.

Osher L.J., P.A. Matson, and R. Amundson, 2003: Effect of land use change on soil carbon in Hawaii. *Biogeochemistry*, **65(2)**, 213-232.

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Table 11A-1. Comparison of net ecosystem exchange (NEE) for different types and ages of temperate forests. Positive NEE means the forest is a sink for atmospheric CO_2. Eighty-one site years of data are from multiple published papers from each of the AmeriFlux network sites, and a network synthesis paper (Law *et al.* 2002). NEE was averaged by site, then the mean was determined by forest type and age class. SD is standard deviation among sites in the forest type and age class.

	NEE (t C ha^{-1} y^{-1})		
	Regenerating Clearcut (–1 ~ 3 years after disturbance) (1 site, 5 site-years)	Young forest (8 ~ 20 years old) (4 sites, 16 site-years)	Mature forest (>20 years old) (13 sites, 60 site-years)
Evergreen Coniferous Forests	–12.7 ~ 1.7, mean –7.1 (SD 4.7) (1 site, 5 site-years)	0.6 ~ 5.9, mean 3.1 (SD 2.6) (4 sites, 16 site-years)	0.6 ~ 4.5, mean 2.5 (SD 1.4) (6 sites, 20 site-years)
Mixed Evergreen and Deciduous Forests	NA	NA	0.3 ~ 2.1, mean –1.0 (SD 0.6) (1 site, 6 site-years)
Deciduous Broadleaf Forests	NA	NA	0.6 ~ 5.8, mean 2.7 (SD 1.8) (6 sites, 34 site-years)

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APPENDIX 11B
PRINCIPLES OF FOREST MANAGEMENT FOR ENHANCING CARBON SEQUESTRATION

The net rate of carbon accumulation has been generally understood (Woodwell and Whittaker, 1968) as the difference between gross primary production (gains) and respiration (losses), although this neglects important processes such as leaching of DOC, emission of methane (CH4), fire, harvests or erosion that may contribute substantially to carbon loss and gain in forest ecosystems (Schulze *et al*., 1999; Harmon, 2001; Chapin *et al*., in review). The net ecosystem carbon balance (NECB) in forests is therefore defined as net ecosystem production, or NEP, plus the non-physiological horizontal and vertical transfers into and out of the forest stand.

With respect to the impacts of forest management on the overall carbon balance, some general principles apply (Harmon, 2001; Harmon and Marks, 2002; Pregitzer *et al*., 2004). First, forest management can impact carbon pool sizes via:

- changing production rates (since NEP = NPP—heterotrophic respiration Rh);
- changing decomposition flows (Rh) (e.g., Fitzsimmons *et al*., 2004);
- changing the amount of material transferred between pools; or
- changing the period between disturbances/ management activities.

The instantaneous balance between production, decomposition, and horizontal or vertical transfers into and out of a forest stand determines whether the forest is a net source or a net sink. Given that these terms all change as forests age, the disturbance return interval is a key driver of stand- and landscape-level carbon dynamics. Rh tends to be enhanced directly after disturbance, so as residue and other organic carbon pools decompose, a forest is often a net source immediately after disturbances such as management activity. NPP tends to increase as forests age, although in older forests it may decline (Ryan, 1997). Eventually, as stands age, NPP and Rh become similar in magnitude, although few managed stands are allowed to reach this age. The longer the average time interval between disturbances, the more carbon is stored. The nature of the disturbance is also important; the less severe the disturbance (e.g., less fire removal), the more carbon is stored.

Several less general principles can be applied to specific carbon pools, fluxes, or situations:

- Management activities that move live carbon to dead pools (such as CWD or soil C) over short periods of time will often dramatically enhance decomposition (Rh), although considerable carbon can be stored in decomposing pools (Harmon and Marks, 2002). Regimes seeking to reduce the decomposition-related flows from residue following harvest may enhance overall sink capacity of these forests if these materials are used for energy generation or placed into forest products that last longer than the residue.
- Despite the importance of decomposition rates to the overall stand-level forest carbon balance, management of CWD pools is mostly impacted by recruitment of new CWD rather than by changing decomposition rates (Janisch and Harmon, 2002; Pregitzer and Euskirchen, 2004). Decreasing the interval between harvests can significantly decrease the store in this pool.
- Live coarse root biomass accounts for approximately 20–25% of aboveground forest biomass (Jenkins *et al*., 2003), and there is additional biomass in fine roots. Following harvest, this pool of live root biomass is transferred to the dead biomass pool, which can form a significant carbon store. Note that roots of various size classes and existing under varying environmental conditions decompose at different rates.
- Some carbon can be sequestered in wood products from harvested wood, though due to manufacturing losses only about 60% of the carbon harvested is stored in products (Harmon, 1996). Clearly, longer-lived products will sequester carbon for longer periods of time.
- According to international convention, the replacement of fossil fuel by biomass fuel can be counted as an emissions offset if the wood is produced from sustainably managed forests (Schoene and Netto 2005).

Little published research has been aimed at quantifying the impacts of specific forest management activities on carbon storage, but examples of specific management activities can be given.

- Practices aimed at increasing NPP: fertilization; genetically improved trees that grow faster (Peterson *et al*., 1999); any management activity that enhances growth rate without causing a concomitant increase in decomposition (Stanturf *et al*., 2003; Stainback and Alavalapati, 2005).
- Practices aimed at reducing Rh (i.e., minimizing the time forests are a source to the atmosphere following disturbance): low impact harvesting (that does not promote soil respiration); utilization of logging residues (biomass energy and fuels); incorporation of logging residue into soil during site prep (but note that this could also speed up decomposition); thinning to capture mortality; fertilization.

Since NECB changes with time as forests age, if a landscape is composed of stands with different ages then carbon gains in one stand can be offset by losses from another stand. The net result of these stand-level changes determines overall landscape-level carbon stores. Note that disturbance-induced Rh losses are typically larger than annual gains, such that a landscape where forest area is increasing might still be neutral with respect to carbon stocks overall. Thus, at the landscape level practices designed to enhance carbon sequestration must, on balance, replace lower-C-density systems with higher-C-density systems. Examples of these practices include: reducing fire losses; emphasizing very long-lived forest products; increasing the interval between disturbances; or reducing decomposability of dead material.

APPENDIX 11B REFERENCES

Chapin, F.I., G. Woodwell, J. Randerson, G. Lovett, E. Rastetter, D. Baldocchi, D. Clark, M. Harmon, D. Schimel, R. Valentini, C. Wirth, J. Aber, *et al*.: Reconciling carbon cycle terminology: a search for consensus. *Ecosystems* (in review).

Fitzsimmons, M.J., D.J. Pennock, and J. Thorpe, 2004: Effects of deforestation on ecosystem carbon densities in central Saskatchewan, Canada. *Forest Ecology and Management*, **188**, 349–361.

Harmon, M.E., J.M. Harmon, W.K. Ferrell, and D. Brooks, 1996: Modeling carbon stores in Oregon and Washington forest products: 1900-1992. *Climatic Change*, **33**, 521–550.

Harmon, M., 2001: Carbon sequestration in forests - addressing the scale question. *Journal of Forestry*, **99**, 24–29.

Harmon, M. and P. Marks, 2002: Effects of silvicultural practices on carbon stores in Douglas-fir-western hemlock forests in the Pacific Northwest, USA: results from a simulation model. *Canadian Journal of Forest Research*, **32(5)**, 863–877.

Janisch, J. and M. Harmon, 2002: Successional changes in live and dead wood carbon stores: implications for net ecosystem productivity. *Tree Physiology*, **22**, 77–89.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey, 2003: National-scale biomass estimators for United States tree species. *Forest Science*, **49(1)**, 12–35.

Pregitzer, K.S. and E.S. Euskirchen, 2004: Carbon cycling and storage in world forests: biomes patterns related to forest age. *Global Change Biology*, **10**, 2052–2077.

Ryan, M.G., D. Binkley, and J.H. Fownes, 1997: Age-related decline in forest productivity: pattern and process. *Advances in Ecological Research*, **27**, 213–262.

Schulze, E., J. Lloyd, F. Kelliher, C. Wirth, C. Rebmann, B. Luhker, M. Mund, A. Knohl, I. Milyukova, W. Schulze, W. Ziegler, A. Varlagin, A. Sogachev, R. Valentini, S. Dore, S. Grigoriev, O. Kolle, M. Panfyorov, N. Tchebakova, and N. Vygodskaya, 1999: Productivity of forests in the Eurosiberian boreal region and their potential to act as a carbon sink - a synthesis. *Global Change Biology*, **5**, 703–722.

Stainback, G.A. and J.R.R. Alavalapati, 2005: Effects of carbon markets on the optimal management of slash pine (Pinus elliottii) plantations. *Southern Journal of Applied Forestry*, **29(1)**, 27–32.

Stanturf, J.A., R.C. Kellison, F.S. Broerman, and S.B. Jones, 2003: Productivity of southern pine plantations – where we are and how did we get here? *Journal of Forestry*, 26–31, April/May 2003.

Woodwell, G. and R. Whittaker, 1968: Primary production in terrestrial communities. *American Zoologist*, **8**, 19–30.