FOREST CARBON SINKS IN THE NORTHERN HEMISPHERE

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Abstract. There is general agreement that terrestrial systems in the Northern Hemisphere provide a significant sink for atmospheric CO_2; however, estimates of the magnitude and distribution of this sink vary greatly. National forest inventories provide strong, measurement-based constraints on the magnitude of net forest carbon uptake. We brought together forest sector C budgets for Canada, the United States, Europe, Russia, and China that were derived from forest inventory information, allometric relationships, and supplementary data sets and models. Together, these suggest that northern forests and woodlands provided a total sink for 0.6–0.7 Pg of C per year (1 Pg = 10^{15} g) during the early 1990s, consisting of 0.21 Pg C/yr in living biomass, 0.08 Pg C/yr in forest products, 0.15 Pg C/yr in dead wood, and 0.13 Pg C/yr in the forest floor and soil organic matter. Estimates of changes in soil C pools have improved but remain the least certain terms of the budgets. Over 80% of the estimated sink occurred in one-third of the forest area, in temperate regions affected by fire suppression, agricultural abandonment, and plantation forestry. Growth in boreal regions was offset by fire and other disturbances that vary considerably from year to year. Comparison with atmospheric inversions suggests significant land C sinks may occur outside the forest sector.

Key words: carbon balance, regional; carbon cycle; carbon sinks and sources; forest carbon budget; forest disturbance; forest inventories; forest products.

INTRODUCTION

Only about half of all carbon dioxide emitted by fossil-fuel combustion and tropical deforestation accumulates in the atmosphere—oceans and the terrestrial biosphere take up the rest (Rayner et al. 1999, Battle et al. 2000, Bousquet et al. 2000, Prentice et al. 2001). The magnitude, location, and causes of terrestrial C sinks have, however, remained uncertain. Observations of atmospheric oxygen concentrations and C isotopes have improved the ability of atmospheric methods to constrain the magnitude of global-scale C uptake by oceans and land ecosystems (e.g., Rayner et

al. 1999, Battle et al. 2000). Inversion studies using atmospheric-transport models indicate that land in the temperate and boreal latitudes of the Northern Hemisphere was a sink for 0.6–2.7 Pg C/yr during the mid 1980s–mid 1990s (Bousquet et al. 1999, Rayner et al. 1999, Battle et al. 2000, Prentice et al. 2001). Temporal patterns of global net C flux are now relatively well understood (Battle et al. 2000, Bousquet et al. 2000), but spatial patterns are more poorly resolved, with considerable variation among studies (e.g., Fan et al. 1998, Bousquet et al. 1999, Rayner et al. 1999). National forest inventories can be used to provide complementary, ground-based estimates of large-scale C balance that can help identify the location of C sources and sinks. Forest inventories are specifically designed to supply statistically sound measurements of timber stocks and growth across large, heterogeneous regions.

TABLE 1. Northern Hemisphere area (millions of hectares) of forest land and other woodland in 1990.

Region	Forested land			Other woodland‡	Total forest and woodland	Forest and woodland as percentage of land area	Reference
	Presently forested	Presently unforested†	Total				
Canada	···	···	316	88	404	44	Kurz and Apps (1999)
United States							Birdsey and Heath (1995)
Alaska	···	···	8	44	52	35	
Coterminous	···	···	204	42	246	32	
Europe§	···	···	149	46	195	36	Kuusela (1994)
Russia‖	764	57	821	66	887	52	Shvidenko and Nilsson (1997)
China	109	11	119	39	157	17	Fang et al. (2001)
Other¶	···	···	92	16	108	15	UNECE/FAO (1992, 2000)
Total			1711	339	2050	36	

† Includes burned, harvested, or plantation land that has not yet regenerated to forest.

‡ Includes open or unproductive dry woodland, taiga, or treeline forest; and for China, oil, seed, or fruit tree plantations (16.1 × 10⁶ ha) and bamboo forest (3.8 × 10⁶ ha). Woodland area for Canada reported here includes all forested areas in the Arctic, Subarctic, and Grassland Ecoclimatic Provinces (Ecoregions Working Group 1989) for which the national forest inventory contains data. It does not include any areas of open woodlands that may exist within the more densely forested regions (Kurz et al. 1992).

§ Countries included: Albania, Austria, Belgium, Bosnia-Herzegovina, Bulgaria, Croatia, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Luxembourg, Macedonia, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom, and Yugoslavia.

‖ Area estimates for Russia pertain to 1993.

¶ Countries included: Japan, North Korea, South Korea, Mongolia, Latvia, Lithuania, Estonia, and the Commonwealth of Independent States other than Russia.

Field measurements exist for more than a million plots across the Northern Hemisphere, and measurements extend back decades in many countries. Comprehensive national forest inventories have not been conducted in most tropical countries, although a few regional surveys have occurred (e.g., Brown and Lugo 1992, Phillips et al. 1998). In most northern countries, total wood volume can be estimated with 95% confidence to within 1–5% of the mean (Powell et al. 1993, Köhl and Päivinen 1997, Shvidenko and Nilsson 1997). Uncertainties increase as raw inventory measurements are converted to C stocks and fluxes for the full forest sector, but the compilation of so many, spatially representative measurements makes inventories a powerful resource for quantifying net C balance across heterogeneous regions. An uncertainty analysis of the net C budget of privately owned U.S. forest ecosystems (~140 × 10⁶ ha) suggests net C flux can be estimated to within ±28 Tg C/yr (Heath and Smith 2000a). In contrast to estimates from eddy-covariance sites or networks, inventory-based C budgets represent the full range of forest types, climate zones, and disturbance and management regimes across the temperate and boreal zone. In contrast to ecosystem models, inventories capture the full range of impacts of human actions and natural disturbance, including forest harvest, fire, insect outbreaks, and land-use change. Recovery from these disturbances has been shown to be the dominant factor driving C accumulation in eastern U.S. forests (Caspersen et al. 2000).

We synthesized forest inventory information for the late 1980s–mid 1990s to estimate C pools, sources, and sinks for the forest sector of the Northern Hemisphere.

We focused on five regions that together cover 95% of the area of northern temperate and boreal forest and woodland: Canada, the United States, Europe, Russia, and China (Table 1). The remaining 5% occurs in the Baltic states, Japan, North Korea, South Korea, Mongolia, and Commonwealth of Independent States other than Russia (UNECE/FAO 1992, 2000). For as much of each region as possible, we report the net change of C stocks in live vegetation, dead organic matter, and forest products. Previous compilations of inventory data have focused on only live vegetation (Armentano and Ralston 1980, UNECE/FAO 2000), or have been superceded by analyses based on improved data and methods for quantifying the effects of disturbance and the dynamics of dead organic matter in several regions (Sedjo 1992, Apps et al. 1993, Dixon et al. 1994, UNECE/FAO 2000).

METHODS

Definitions of "forest" and "woodland" vary from country to country, with *forests* generally defined as land with a minimum tree cover (typically 10–30%), patch size (typically 0.1–0.4 ha) or productivity (typically 1.0–2.0 m³·ha⁻¹·yr⁻¹). Areas reported here include those areas of forest or woodland that have been disturbed by harvest, fire, or other factors (Table 1). *Woodlands* are variably defined, but are generally less densely forested and less productive than forests, and can include savanna woodland, subalpine forest, and taiga. In most countries, woodlands have been less thoroughly inventoried than productive forests; we present estimates of changes in woodland C stocks only for those regions for which we had sufficient data.

Several steps are required to convert inventory measurements to C balance of the full forest sector. Timber stocks and growth are nearly always reported in terms of growing-stock volume, which is the volume of the bole portion of trees that exceed a threshold diameter. To convert from growing stock volume to estimates of the C content of all forest vegetation (i.e., bole, branches, foliage, bark, stump, coarse and fine roots), conversion factors or regression equations have been developed from extensive measurements of plant biomass and allometry. Understory vegetation usually makes up a very small fraction of stand biomass, and was estimated from separate data sets (e.g., Birdsey [1992] and Birdsey and Heath [1995] for the United States), or by direct extrapolation from growing stock data (e.g., Fang et al. [1998] for China, Lakida et al. [1997] and Shepashenko et al. [1998] for Russia). Estimates of C stocks in Canadian forest vegetation include understory trees, but not herbs, shrubs, or mosses (Kurz and Apps 1999). The development of highly detailed, species- and region-specific conversion factors for Russia (e.g., Lakida et al. 1997, Shepashenko et al. 1998) and China (Fang et al. 1998), included in this review, has substantially refined previous estimates of forest C stocks and changes for these regions (e.g., Armentano and Ralson 1980, Sedjo 1992, Dixon et al. 1994).

Methods of quantifying the dynamics of vegetation C stocks have also improved. Changes in vegetation C stocks reported here were quantified with combinations of sequential inventories and age-class yield models derived from inventory data, with the choice of method based on the information available for each region. Estimates from sequential inventories automatically integrate the effects of all factors influencing tree growth, from losses caused by harvests and natural disturbances to gains from improved forest management or altered environmental conditions (e.g., climate change, atmospheric CO_2 or N fertilization). Age-class yield models use inventory data to derive average per hectare yield tables or biomass curves by age class and forest type. The area of forest in different age classes is then tracked through time, while also accounting for mortality through harvest and natural disturbances. The validity of the age-class yield models is then checked against data from subsequent inventory updates. If not updated with new survey data or other adjustments, yield models will not capture potential changes in growth due to altered climate or other environmental conditions. Age-class yield models are especially useful in forests that experience stand-replacing disturbances such as fire, severe insect outbreaks, or clearcut harvest.

Estimates of the change in live biomass of forests in China were obtained from Fang et al. (2001), who used growing-stock volume data from sequential inventories and previously developed C conversion factors (Fang et al. 1998). We used a similar approach to estimate the stock and change in live biomass in woodlands in China. Estimates of wood increment in European forests were taken from sequential FAO reports (Kuusela 1994, UNECE/FAO 2000), and converted to C with simple conversion factors (Houghton et al. 1996). The variety and complexity of inventory systems in Europe makes synthesis of this information particularly challenging (e.g., Köhl and Päivinen 1997, Nabuurs et al. 1997, UNECE/FAO 2000). We have not included European woodlands ($\sim$40–46 $\times$ 10^6 ha); data in UNECE/FAO (2000: Tables 33, 40, 42, and 47) suggest that the net increase of vegetation C stocks in European woodlands is very small ($\sim$2 Tg C/yr), although the thoroughness with which woodlands are inventoried varies greatly by country (Kuusela 1994). Carbon uptake by forests in the coterminous United States was largely derived from sequential inventories, supplemented by age-class models for years between inventories (Birdsey and Heath 1995, U.S. Department of State 2000). Estimates of C stocks exist for Alaskan forests and taiga woodlands (52 $\times$ 10^6 ha) and for unproductive woodlands of the coterminous United States (42 $\times$ 10^6 ha, mostly western pinyon–juniper forests; Birdsey and Heath 1995), but sufficient data were not available to reliably quantify changes in C stocks for these regions; we include estimates only for continental U.S. timberlands (198 $\times$ 10^6 ha; U.S. Department of State 2000). As described elsewhere in detail, estimates of biomass accumulation in closed forest, open woodland, and recently disturbed areas in Canada (Kurz and Apps 1999) and Russia (Nilsson et al. 2000, Shvidenko et al. 2000, Shvidenko and Nilsson, in press) were derived from syntheses of available inventory data, stand models, and information on the extent and dynamics of forest disturbances by fire, insects, and harvests.

Carbon stocks and sinks in forest products and landfills were modeled from data on harvest removals, recycling rates, conversion efficiencies to various wood products, and residence times of products in use and in landfills for Canada (Apps et al. 1999), Russia (Obersteiner 1999, Nilsson et al. 2000), and the United States (Skog and Nicholson 2000). Stocks and sinks of wood products in Europe were modeled from harvest data (Kuusela 1994) and a simple two-pool model of production and turnover; landfills were not included (G.-J. Nabuurs, A. Pussinen, M. J. Schelhaas, and G. M. J. Mohren, unpublished manuscript). Wood product sink estimates reported here do not represent only the wood products derived from a region's forests (which may be exported), but rather they pertain to the net change in the C stock of forest products in use and in landfills within a region, explicitly accounting for the net import/export balance. This distinction makes a large difference for Canada, which has exported two thirds of its cumulative pool of wood products (Apps et al. 1999).

Dead organic matter in forest and woodland ecosystems includes dead wood (above- and belowground

TABLE 2. Northern Hemisphere carbon pools in the forest sector, 1990.

Forest C pools (Pg C)	Forested land				Other woodland			
	Live veg.	Dead wood	Forest floor	SOC	Live veg.	Dead wood	Forest floor	SOC
Canada	12.9	3.5	7.7	37.8	1.6	0.6	1.8	18.7
United States								
Alaska	0.6	†	0.5	3.7	1.7	†	1.2	8.3
Coterminous	12.7	†	2.6	18.9	1.6	†	0.3	2.4
Europe§	7.7	1.0	0.7	13.0	0.2	n.a.	n.a.	n.a.
Russia	33.7	8.9	12.0	127.2	0.6	0.4	0.7	8.5
China	4.6	n.a.	0.9	21.0	0.6	n.a.	n.a.	n.a.
Other§	4.7	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Totals‖	77	13	24	222	...	...	...	...
Percentage total forest + woodland area included in C pool totals:								

Notes: Key to abbreviations: Live veg. = live vegetation, including above- and belowground components of trees as well as understory vegetation; Dead wood = aboveground coarse woody debris and dead woody roots from both natural causes and from harvest operations; For. floor = forest floor or the O horizon; SOC = soil organic carbon from below the O horizon to a depth of 1 m; Forest prod. = forest products both in use and in landfills; n.a. = not available.

† Stocks of carbon in logging debris are included with forest floor; naturally produced dead wood was not quantified.

‡ Alaska forest products are included with the coterminous United States.

§ For countries included in Europe and Other, see Table 1.

‖ When several cells in a column have no data, no total is given. Other totals are rounded to the nearest petagram.

dead wood from both harvests and natural mortality), the forest floor, and soil organic carbon (SOC). Estimates of the stocks of C in dead wood and the forest floor reported here were derived from varying combinations of measurements from the ecological literature and simple bookkeeping or ecosystem models driven by inventory information. Supplementary data bases were used to estimate SOC stocks to a depth of 1 m. See the references in Table 2 for additional details on how these pools were quantified.

Estimates of changes of dead organic-matter pools are much less certain than estimates of changes in vegetation C, but have improved considerably and can be constrained by observed patterns of tree growth, harvest, and mortality. Previous estimates of forest C sinks have excluded consideration of changes in dead organic-matter pools (Armentano and Ralson 1980, UNECE/FAO 2000), or have often assumed that these stocks increase in direct proportion to increases in tree biomass (Johnson and Sharpe 1983, Kauppi et al. 1992, Sedjo 1992, Birdsey and Heath 1995), an assumption that can greatly distort the increment of dead organic-matter pools. Estimates of the net change in dead organic-matter pools reported here were derived with several methods; all include some accounting for long-term changes in land use or productivity, but none include the interannual effects of climate variation on decomposition. For Canada, changes in dead organic-matter pools were dynamically modeled by calculating

the difference between inputs to and losses from four pools: dead boles, dead branches and coarse roots, foliar and fine-root litter, and humus (Kurz and Apps 1999). Inputs include litter, harvest slash, disturbance-killed biomass, and natural morality through stand development; losses occur through fire and decomposition (Kurz et al. 1992, Kurz and Apps 1999). A similar modeling approach was used to estimate the changes in dead organic matter in Europe, although estimates were spatially aggregated and the modeled humus pool was split into fast and slow soil C pools (G.-J. Nabuurs, A. Pussinen, M.-J. Schelhaas, and G. M. J. Mohren, *unpublished manuscript*). For the United States, forest floor and SOC pools were previously assumed to increase in proportion to increases in vegetation C stocks (Birdsey and Heath 1995, Heath and Smith 2000b). Values reported here (and in U.S. Department of State [2000]) were estimated by tracking changes in forest floor and soil C pools associated with changes in land use and forest management, similar to the bookkeeping approach of Houghton et al. (1983). The estimate of change for the U.S. dead-wood pool includes only modeled estimates of the balance of production and decomposition of logging debris; carbon sinks in naturally produced dead-wood pools are not included in the present set of calculations (U.S. Department of State 2000). For Russia, estimates of dead-wood stocks were compiled from partial inventory measurements and large ecological data sets, with changes in this pool

TABLE 2. Extended.

Overall forest sector						References
Live veg.	Dead wood	Forest floor	SOC	Forest prod.	Total	
14.5	4.1	9.5	56.5	0.3	85	Kurz and Apps (1999); Apps et al. (1999) (For. prod.)
2.4	†	1.6	12.0	‡	16	Birdsey and Heath (1995)
14.4	†	2.9	21.3	2.8‡	41	Birdsey and Heath (1995); Skog and Nicholson (2000) (For. prod.)
8.0	1.0	0.7	13.0	0.5	23	UNECE/FAO (2000) (Live veg.); Nabuurs et al. (1997) (SOC); G.-J. Nabuurs et al., *unpublished manuscript* (see Fig. 1) (Dead wood, For. floor, and For. prod.)
34.3	9.3	12.7	135.7	0.7	193	Shvidenko et al. (2000) (Forested land: Live veg. and Dead wood); Nilsson et al. (2000); Obersteiner (1999) (For. prod.)
5.2	n.a.	0.9	21.0	n.a.	27	Fang et al. (2001) (Forested land: Live veg. only); Zhou et al. (2000) (For. floor and SOC); authors' calculation (Woodland and Overall: Live veg.)
4.7	n.a.	n.a.	n.a.	n.a.	5	UNECE/FAO (1992, 2000) (Live. veg)
83	14	28	260	4	390	
100	85	91	91	87		

modeled dynamically as the balance between inputs of dead wood (from disturbances, harvests, and natural morality), and losses from decomposition (Shvidenko and Nilsson, *in press*). Changes in the forest floor were estimated as a function of the relative amount of disturbed forest area each year. Soil C sinks were estimated as the balance between humification processes and soil solution export (Nilsson et al. 2000); estimates reported here do not include increases in the forest soil C pool due solely to increases in the area of land classified as forest land. Estimates of litter and soil C stocks in China were obtained from Zhou et al. (2000), but we did not have sufficient data to calculate changes in forest product or dead organic-matter pools for China or for several smaller Eurasian countries.

RESULTS

Forests and woodlands covered 2×10^9 ha in the Northern Hemisphere (Table 1) and contained 83 Pg C in live vegetation in 1990 (Table 2). Dead wood in this region (excluding several small Eurasian countries) contained 14 Pg C; the forest floor, 28 Pg C; and soil organic matter, 260 Pg C (Table 2). Over the last several decades, C stocks in live vegetation increased steadily in the coterminous United States, Europe and European Russia, with more recent decreases in Canada and Asian Russia (Fig. 1). Together, these changes amount to a net increase in live-tree C stocks of ~0.21 Pg C/yr during the late 1980s to early 1990s (Fig. 2). In the United States, tree C accumulated largely in the east, where the rate of regrowth from agricultural abandonment and past harvests exceeded the harvest rate (Heath and Birdsey 1993, Birdsey and Heath 1995). Carbon was also accumulating in vegetation in the relatively managed forests of Europe, European Russia, and China. In contrast, vegetation C stocks in the largely unmanaged boreal forests of both Canada and Asian Russia declined in the late 1980s and early 1990s (Fig. 1) due to large disturbances. Canada experienced extensive insect outbreaks in the late 1970s and large fires in the late1980s and early 1990s (particularly 1989, 1991, 1994, and 1995) relative to the pre-1970 average. Unusually large fires in eastern Russia in 1987–1989 caused vegetation C stocks to decline during 1988–1992, despite a net increase over the last several decades (Fig. 1). This episodic mortality produced large quantities of dead wood that will continue to release
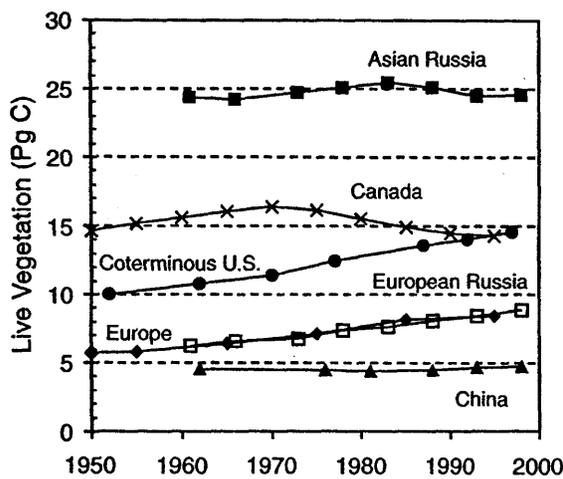

FIG. 1. Carbon stocks in live forest vegetation over the last half century in Canada (Kurz and Apps 1999), the coterminous United States (Birdsey and Heath 1995), Europe (G.-J. Nabuurs, A. Pussinen, M.-J. Schelhaas, and G. M. J. Mohren, *unpublished manuscript*), Russia (Shvidenko and Nilsson, *in press*), and China (Fang et al. 2001).
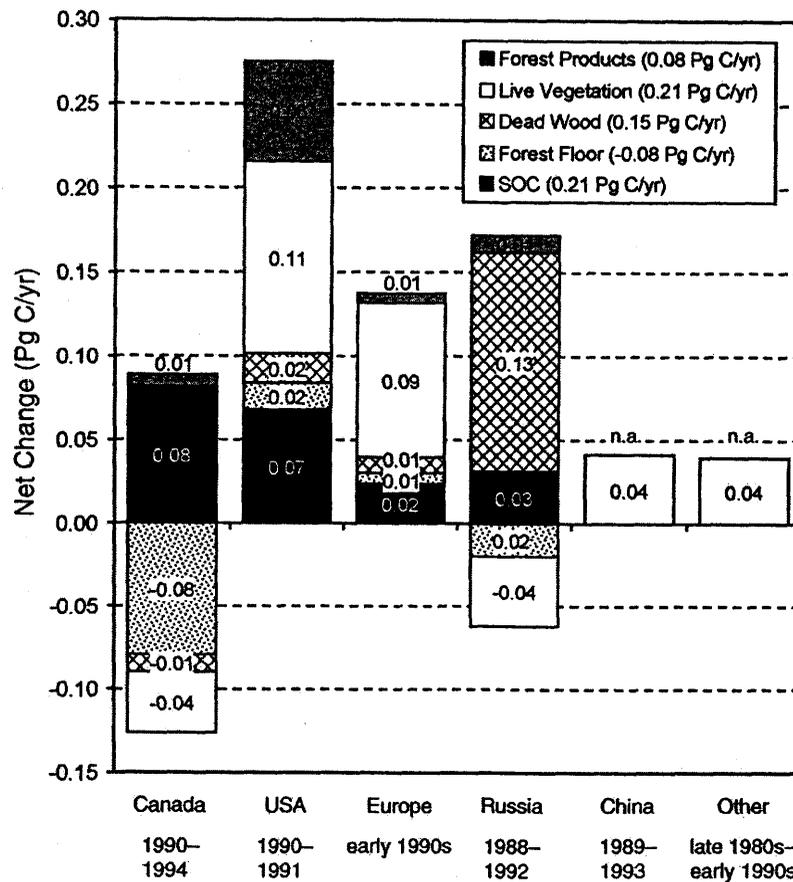
FIG. 2. Net change in forest-sector carbon pools. Positive values represent carbon sinks, and negative values represent carbon sources to the atmosphere. Dates are inclusive. Change statistics for the coterminous United States and Europe do not include woodlands; change statistics for "other" countries (80 × 10⁶ ha) include Japan, the Baltic states, and the Commonwealth of Independent States other than Russia. SOC = soil organic carbon; "n.a." indicates that data were not available.

C to the atmosphere for many decades as it decomposes. Estimated production of dead wood in Russia due to disturbances, harvests, and within-stand mortality during 1988–1992 exceeded modeled dead-wood decomposition, forming a large (0.13 Pg C/yr), temporary C sink (Fig. 2). In Canada, where large disturbances occurred many years earlier than in Russia, modeled decomposition of dead wood from past disturbances exceeded estimated production of dead wood during 1990–1994. Total accumulation of dead wood across the northern temperate and boreal zone amounted to a sink of about 0.15 Pg C/yr during the late 1980s–early 1990s. Net accumulation of harvested wood in the form of long-lived forest products and in landfills represents an additional C sink in the forest sector of about 0.08 Pg C/yr combined within Canada, the United States, Europe, and Russia for the late 1980s–early 1990s (Fig. 2). In the mid- and late 1990s, declines in forest harvest rates in Russia caused the Russian forest product pool to switch from a small C sink to a small source (Obersteiner 1999, Nilsson et al. 2000).

Changes in forest floor and SOC pools are the least certain components of the budgets because these pools have not been routinely measured in any of the inventories. Modeled losses of forest floor material in Canada and Russia exceeded modeled accumulation in the United States and Europe, such that the forest floor was estimated to be a net source of about 0.08 Pg C/yr across the northern temperate and boreal zone. For soil organic carbon (SOC), the best modeled estimates available at present suggest that SOC is accumulating 0.21 Pg C/yr through incorporation of dead organic matter from past disturbances in Canada, through long-term humification processes in Russia, through reversion of agricultural lands to forest in the United States, and through increased forest productivity in Europe. Unfortunately, all of these processes are not modeled using a common framework and so it is difficult to directly compare estimates and their uncertainties. We do not have data on changes in vegetation C pools for 9% of the region's 2050 × 10⁶ ha, or for changes in forest product or dead organic-matter stocks for 20%
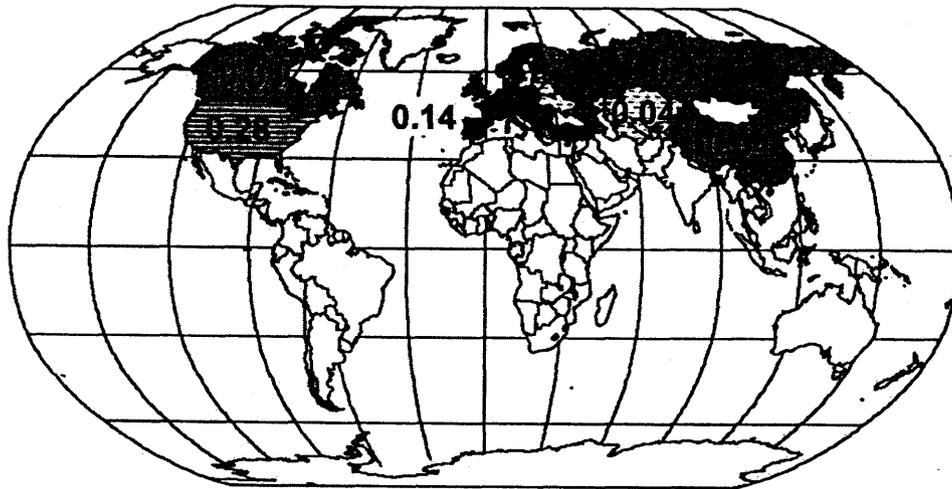
FIG. 3. Forest-sector net carbon sources (−) and sinks (+); the data are petagrams of C per year. The dagger symbols indicate net change in tree stocks; other values pertain to the entire forest-sector balance.

of the region; if we extrapolate mean C accumulation rates to these areas, then we expect that net changes in these unmeasured pools were ≤0.1 Pg C/yr.

DISCUSSION

Taken together, forest inventory C budgets indicate that the forest sector of the northern temperate and boreal zone accumulated about 0.6 Pg C/yr in the late 1980s–early 1990s (Fig. 3), with perhaps an additional 0.1 Pg C/yr of accumulation in regions for which few data were available. Over half of the observed C sink occurred in Eurasia (Fig. 3). The coterminous United States, Europe, China, and small Eurasian countries contained one third of the region's forest and woodland area, but accounted for at least 80% of the observed C sink. The disproportionate sink in temperate regions relative to boreal regions likely reflects the temperate zone's legacy of large-scale land-use management and change over the last century, and fire-suppression policies in recent decades. Growth rates in unmanaged forests of the eastern United States have changed little over the past several decades, suggesting that nearly all of the C accumulation in this region is due to forest regrowth from past disturbance rather than to growth stimulation by increased atmospheric CO_2, N deposition, or climate change (Caspersen et al. 2000). Growth rates in many European forests have increased over the last several decades, but it is not yet clear whether these increases are due to altered environmental conditions or to improved forest management (Spiecker et al. 1996). Carbon accumulation in China is likely due to its extensive afforestation efforts, as 80% of the observed increase in tree C stocks in China occurred on its 21×10^6 ha of forest plantations (Fang et al. 2001). Across the temperate zone, these extensive changes in land-use patterns and forest management have likely contributed greatly to the region's observed C sink.

In contrast, growth in the relatively unmanaged boreal forests of Canada and eastern Russia was offset by an increase in disturbances during the late 1980s–early 1990s. This conclusion differs markedly from previous syntheses of forest inventories that suggested Canadian and Russian forests were sinks for 0.4–0.6 Pg C/yr (Armentano and Ralson 1980, Sedjo 1992, Apps et al. 1993, Dixon et al. 1994, UNECE/FAO 2000), and results almost entirely from improved methods of quantifying the impacts of disturbances. Improved simulation of dynamic responses to disturbances led to the conclusion that Canada's forests were a source of C to the atmosphere during the late 1980s and early 1990s (Kurz and Apps 1999), rather than a small sink, as suggested by previous simulations with a static version of the Canadian forest model (Kurz et al. 1992). For Russia, forest C balance has previously been estimated from nonrepresentative ecological sample plots (Kolchugina and Vinson 1993b) and from application of C accumulation rates measured in U.S. forests (Kolchugina and Vinson 1993a). These two estimates, along with the static estimate of C sinks in Canada, and very preliminary estimates of C balance for China were compiled by Dixon et al. (1994) to estimate net C balance for northern temperate and boreal forests for the late 1980s. Other estimates of C uptake in Russian and Canadian forest vegetation for the mid- to late 1990s (UNECE/FAO 2000) were calculated from average growth rates over the lifespan of the forest rather than current growth rates (i.e., mean rather than current annual increment), an approach that integrates growth over many decades but can largely miss effects of decreases in forest biomass caused by fire and other disturbances that are so important in the dynamics of these ecosystems (Kurz and Apps 1999, Shvidenko and Nilsson 2000).

The present synthesis of inventory-based estimates

of C sinks includes several sources of uncertainty, but it strongly constrains estimates of forest sector C uptake toward the low end of the 0.6–2.7 Pg C/yr of net C uptake indicated by atmospheric inversions for this region (Bousquet et al. 1999, Rayner et al. 1999, Battle et al. 2000, Prentice et al. 2001). To achieve rates of net C uptake at the middle to high end of this range, substantial C sinks must exist outside of the forest sector, as indicated by recent land-based analyses in the United States (Houghton et al. 1999, Pacala et al. 2001). Woody encroachment, recent agricultural practices, riverine transport and sedimentation, and grain export may amount to 0.2–0.3 Pg C/yr of net C removal from the atmosphere within the United States, approximately doubling the sink observed in the forest sector alone (Pacala et al. 2001). Although atmospheric techniques excel at detecting interannual changes in net terrestrial C uptake (Battle et al. 2000, Bousquet et al. 2000), inventories integrate changes in forest C stocks over several years, minimizing the influence of climate variability yet capturing factors affecting long-term C balance. Additional comprehensive inventories—in partially inventoried woodlands, in tropical regions, and outside the forest sector—will help reduce uncertainties over the location and magnitude of terrestrial C sinks. To predict the future trajectory of C sinks on land, inventory-based C budgets must be integrated into a framework that also includes atmospheric models, manipulative experiments, ecosystem models, and studies of land-use change.

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