#2294

Olga N. Krankina, Mark E. Harmon and Jack K. Winjum

Carbon Storage and Sequestration in the Russian Forest Sector

Research on country-level carbon budgets provides a quantitative basis for national policy decisions on greenhouse gas mitigation strategies. For many countries, including Russia, the carbon pools and flux associated with the forest sector are important components of the national carbon budget. Russia has 884 mill. ha of forest storing an estimated 42.1 PgC in live biomass, 29.5 PgC in detritus, and 2.9 PgC in forest products. Between 1988 and 1993, carbon stores in live biomass were reduced by 0.5 Pg as a result of the timber harvest (which exceeded carbon accumulation in growing trees), fires, and other natural disturbances. Only a small portion of the disturbed forest carbon pool is instantly released into the atmosphere: the greater part of it is transferred into the detrital pool while some is accumulated in forest products. The lack of data on these key components leads to large uncertainties in carbon flux estimates. Russian forests have significant potential to be managed for the purposes of carbon sequestration. The analysis indicates that forest management measures can increase the future level of carbon storage in Russian forests on a sustainable basis by 2.0 PgC, approximately 2.8%.

INTRODUCTION

The United Nations Framework Convention on Climate Change, which was signed by 153 nations at the 1992 Rio de Janeiro Conference on Environment and Development, requires ratifying countries to conduct national inventories of anthropogenic sources and sinks of greenhouse gases (GHG). For many countries, the carbon pools and flux associated with the forest sector are important components of the national carbon budget. Large-scale carbon budgeting has been widely used in recent years to analyze the carbon status of countries, regions, biomes, and sectors of the economy (1–5). This budgeting process requires accounting for all the relevant carbon pools, pathways, and fluxes within a single framework. In forest biomes, this framework can be quite consistent across geographical zones, thus allowing comparisons of results and aggregation at the global level (6).

Globally, forests play a major role in the carbon cycle because they account for a greater part of the carbon exchange between the atmosphere and terrestrial biosphere than any other ecosystem type (6). Thus, the status and management of forests largely determines whether a terrestrial biosphere is a net sink or net source of carbon. To date, the carbon flux from forests appears to have been released to the atmosphere, with 90 to 120 Pg of carbon released from 1850 to 1980 (7). This flux is largely a response to population growth, since people clear forests for agriculture and are dependent on forests for construction materials, fuel, food, and fiber. Agricultural clearing and the increasing demand for forest products have caused extensive deforestation and expansion of forest management in many parts of the world. Currently, it is estimated that only 10% of the world's forests are actively managed (8). In the future, forest management activities are likely to expand, which could significantly affect the carbon status of the world's forest ecosystems. It has been shown that forests in most boreal, temperate, and tropical regions can be managed to conserve and sequester carbon in the terrestrial biosphere (4, 9, 10). For this reason, many national plans aimed at stabilization of GHG emissions specifically identify CO_2 sequestration by natural sinks, including forests, as an important component of climate change mitigation strategies.

PURPOSE

The purpose of this paper is to: (*i*) review and analyze existing data on the carbon balance of Russian forests; (*ii*) identify major uncertainties in current carbon budgets; (*iii*) evaluate recent forest sector trends that affect the carbon balance of Russian forests; and (*iv*) examine promising management practices that can increase carbon storage and sequestration. Although we examine only the Russian forest sector in this paper, many of the issues addressed are applicable to any forest region of the globe.

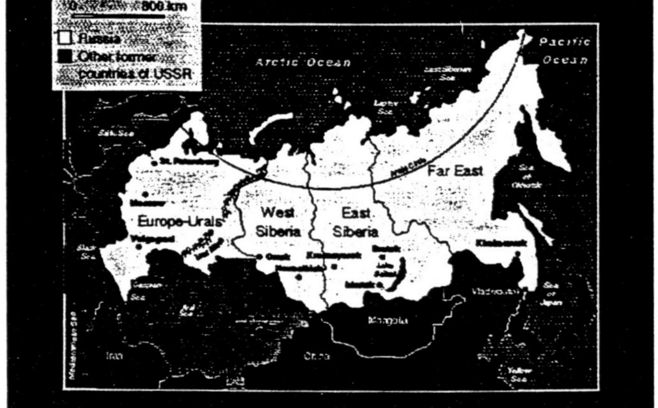
BACKGROUND

Russia is an important case study in carbon cycling because its forest sector covers a very large area, 884 mill. ha (Fig. 1). As such, it accounts for over 20% of the world's forest area and about 50% of all boreal forests (11). This vast expanse of land, occupying over 45% of Russia's land area, is covered mostly by boreal (taiga) forests on podzol soils. The forests are dominated by a limited number of coniferous tree species: Scots pine (*Pinus sylvestris*) and spruce (*Picea excelsea*) to the west of the Ural Mountains; and larch (*Larix sibirica, Larix dahurica*), pine (*Pinus sylvestris, P. sibirica*) and fir (*Abies sibirica*) in Siberia (12).

Forests of Europe-Urals comprise 26% of Russia's total forest area and have been intensively harvested for many decades. At present, 61% of the harvesting, 73% of the timber consumption, and most of the forest management activities are still concentrated there (13). It is in this European part of Russia that the anthropogenic effect on forests is most pronounced.

East of the Urals, the abundance of forest resources increases, but management activities are limited to the land around major population centers. Forests in Siberia and the Russian Far East occupy an area the size of the continental US. These are largely natural forests at different stages of recovery after wildfires, with mature and overmature stands comprising nearly 50% of all Russian forest land (11).

Figure 1. Geographic regions of Russia.



In an effort to assess the amount of carbon stored in Russian forests and the impact of the forests on atmospheric CO_2, several studies were recently performed (2, 4, 14, 15). These studies indicate that Russian forests store 29.5–50.4 Pg of carbon in live biomass with an annual net carbon sequestration rate estimated at 0.06–0.49 Pg (Table 1). The estimates of forest biomass and productivity are based on two types of data: forest inventory statistics and ecological sample plots combined with vegetation maps. The advantage of using forest inventory data for Russia is that they provide consistent information on the extent of forest-land area in the entire country and detailed data on wood volume for 87.5% of the forests under state forest management (11). The inventory of state forest land is performed every 10–15 years and includes stand mapping using aerial photographs and a ground survey of each mapped polygon ranging in size from 1 to 50 ha. A standard set of measured parameters includes site characteristics, tree species composition, mean tree characteristics (height, diameter, and age), canopy structure, wood volume, and characteristics of the different types of land without tree cover (clearcuts, bogs, meadows, etc.). Stand-level data is aggregated at the ranger district, forest, and regional (oblast, kray, etc.) levels. Published summaries for regions contain information on forest area and wood volume distribution by dominant tree species, productivity and stand density classes, age groups, and management categories (11, 16). Unfortunately, data on biomass components other than stemwood are not included in these inventories. To convert forest inventory parameters into biomass carbon values a set of conversion factors is needed (14). Some factors are available and fairly stable (e.g., wood density, carbon content of biomass); others, such as the proportion of dead wood or roots in total biomass, are highly variable and the data for them are scant or unavailable. Alexeev and Birdsey (14) published a thorough and detailed description of methods used to calculate carbon pools based on Russian forest inventory statistics and applicable conversion factors.

Another major source of data for carbon budget calculations is ecological sample plots. They usually have mostly complete biomass inventories; however, they are set up for different purposes and are not intended to represent an entire forest type. Such data were aggregated and summarized by Bazilevich for over 1500 plots in Russia (17). The greater part of these ecological sample plots was set up for the *Man and Biosphere* (MAB) program in the 1970s. These plots represent natural undisturbed stands of high productivity, not the actual averages. Many frequently overlooked or difficult-to-measure parameters are poorly represented. Nevertheless, this plot database is the best current source of information available for calculating potential biomass stores (assuming no disturbance or management impact) and deriving conversion factors for converting forest inventory parameters into biomass stores and accumulation rates.

METHODS

The calculation of forest biomass carbon pools in this analysis is based on four estimates of the Russian forest carbon budget (2, 4, 14, 15). Our review showed that all four of these estimates used the same forest inventory data updated to 1 January, 1988 (11), and independently arrived at fairly consistent estimates of live forest biomass (Table 1). This allowed for the calculation of a mean value of this parameter and an average ratio of live biomass carbon-to-wood volume. This ratio was used to calculate live biomass carbon stores in

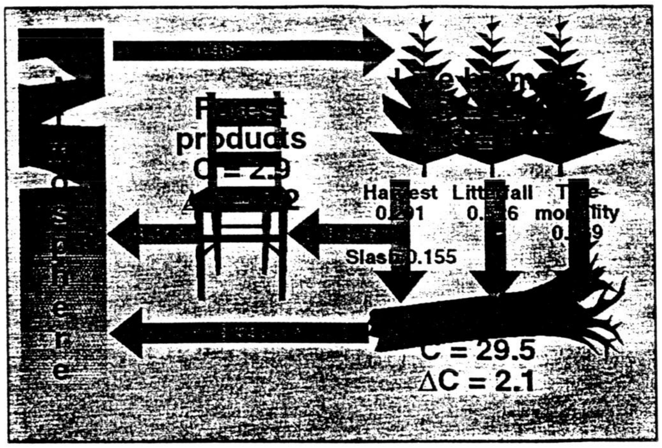


Figure 2. Carbon budget of the Russian forest sector: carbon pools in 1988 (C) in PgC; changes in carbon pools between 1988 and 1993 (DC) in PgC; and carbon fluxes in PgC yr^{-1}.

1993 based on the most recent forest inventory data (16) and thus assess the change in the live biomass carbon pool for the period between 1988 and 1993. Other parameters for the carbon budget of the Russian forest sector between 1988 and 1993 (Fig. 2) were calculated using the respective forest inventory summaries (Table 2) and conversion factors derived from recent publications. Carbon accumulation in live biomass of closed forest stands, for example, was calculated based on 822 mill. m^3 of annual wood increment, 1.15 crown factor, 0.4 wood density, 3.58 wood-to-biomass increment conversion factor, and 0.5 biomass to carbon conversion factor (11, 14, 16, 17). Carbon accumulation on lands for which wood increment is not reported (young and open forest stands and forest lands currently without tree cover) was calculated separately based on plot data (17, 18). Litter-fall was assessed similarly. Carbon removed by timber harvest was calculated based on an average timber harvest of 389 mill. m^3 (19). Carbon flux associated with tree mortality was computed as the difference between other fluxes: carbon accumulation in live biomass minus harvest minus litterfall plus annualized carbon loss from live biomass pool (Fig. 2). The detrital pool including litter, dead wood, and slash is an average based on published data (2, 4, 14). Carbon retention in this pool over the 5-year period assumes no net litter accumulation and a

Table 1. Estimates of carbon stores (PgC) and net carbon accumulation (PgC yr^{-1}) in Russian forests.

Source	Live forest biomass	Detritus	Soils	Peat	Net Carbon accumulation
Alexeev and Birdsey, 1994 (14)	29.5	31.4	72.5	54.0	Not available
Isaev et al.. 1993 (15)	41.2	Not available	Not available	Not available	0.21
Kolchugina et al. 1992 (2)	50.4	30.4	214.4	138.0	0.49
Krankina and Dixon, 1994 (4)	47.1	26.0	106.1	Not available	0.06

Table 2. Forest resources and carbon stores in Russia (11, 16).

Parameters	1988	1993	Change (1988–1993)
Forest land area, mill. ha	884.1	886.6	2.4
Closed forest area, mill. ha	771.1	763.5	−7.6
Growing stock, thousand mill. m^3 of wood (Pg C in live forest biomass)*	81.6 (42.1)	80.7 (41.6)	−0.9 (−0.5)
Growing stock of mature and old-growth forest, thousand mill. m^3 of wood (Pg C in live forest biomass)*	47.7 (24.6)	44.1 (22.8)	−3.6 (−1.8)
Mean annual increment of live wood, mill. m^{-3}	822	822	0

*Based on 0.516 live biomass carbon to timber volume ratio (mean value from 2, 4, 14, 15).

dead wood decomposition rate of 3.3% yr^{-1} (20). Carbon accumulation and release in the forest products section presumes that 28% of material entering this pool is lumber, 44% is short-lived forest products (plywood, particle-board, etc.), and 28% is paper products (21) with annual decomposition rates of 1%, 5%, and 30%, respectively (22). Carbon transfer from detritus into soil was considered insignificant on the time scale of five years.

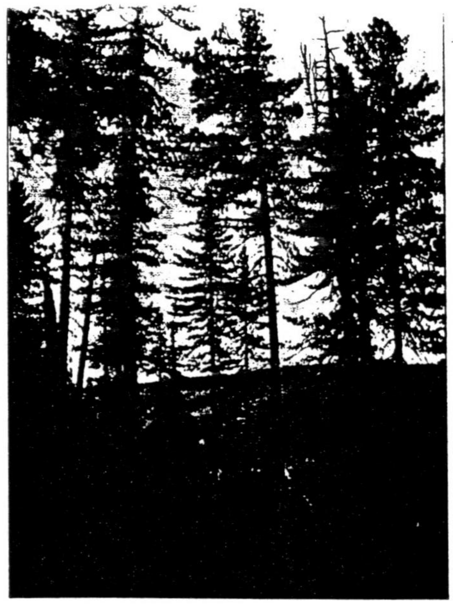
Forest-management practices currently in use were considered from the point of view of their carbon sequestration and conservation potential. The concept of Mean Carbon Storage (MCS) (23) was used to evaluate the effect of forest-management practices on carbon storage and sequestration. MCS presumes that each management scenario or practice is maintained over an indefinite number of rotations without a reduction in productivity. MCS is the average value of carbon stored on the site over one full harvest rotation. This approach does not include carbon in durable wood products so the estimates are conservative. The use of an MCS parameter eliminates the need to account for the dynamics of carbon accumulation and release over the rotation period and allows researchers to estimate the amount of carbon that can be stored on a sustainable basis. It is assumed that forest plantations will be harvested on a 100-year rotation and intensively managed including site preparation, thinning, and salvage of natural mortality. For plantations on productive forest and agricultural lands (e.g. clearcuts, glades, forests killed by disturbance, and shelterbelt plantations), the MCS was estimated at 36 MgC ha^{-1} based on the maximum potential carbon storage on a moderately high-quality site and following the procedures described in World Resource Review (24). For the less productive land that is available for forest plantations (sands, drained peat bogs, mine tailings, etc.), an MCS of 18 MgC ha^{-1} was assumed (Table 3). Silvicultural measures on managed forest land of 96.8 mill. ha can increase the MCS by 10% or 3.6 MgC ha^{-1} (4). Assuming that proper fire management can reduce the current area of burned and therefore dead stands (26.5 mill. ha (11)) by 50% and maintain the additional MCS of 36 MgC ha^{-1} on this area, the effect of fire control was calculated. Improved timber utilization that increases product recovery by 25% allows for an extension of harvest rotation on managed forest lands by 25% (e.g. from 80–100 years) increasing the MCS in managed forests by 12% or 4.3 MgC ha^{-1} (24).

RESULTS

In the past few years, a number of research teams worked independently on estimating carbon storage and sequestration in Russian forests using many of the same data sources including forest inventory data updated to 1 January, 1988 (Table 1). The resulting estimates are consistent and indicate that the average value of the carbon pool in live biomass is 42.1 PgC. Similarly, the carbon pool in detritus is 29.5 PgC. Thus, the total biomass pool in forest ecosystems is 71.6 Pg C. This pool is distributed over 884 mill. ha of forest land which represents an average carbon density of 81 MgC ha^{-1} including 47.6 MgC ha^{-1} in live biomass. The average live biomass carbon-to-wood volume ratio is 0.516 MgC m^{-3}.

Recently published forest inventory data updated to 1 January, 1993 (16) indicate that over the 5-year period the forest area in Russia has expanded by 2.4 mill. ha, while the area of closed forest stands has been reduced by 7.6 mill. ha (Table 2). The total reduction in wood volume is 900 mill. m^3 which indicates a net loss of 0.5 PgC from the live biomass carbon pool between 1988 and 1993. In the mature and overmature forest category, the reduction of wood volume is 3.6 thousand mill. m^3. Wood accumulation in growing stands averaged 822 mill. m^3 which indicates a net carbon accumulation of 0.966 PgC yr^{-1}.

Analysis of data on carbon accumulation in live biomass and the net loss of carbon from this pool between 1988 and 1993, within the framework of the forest sector carbon budget (Fig. 2), indicates that tree mortality and timber harvest transferred 0.339 and 0.155 PgC yr^{-1}, respectively, from the live biomass to the detrital carbon pool. A significant proportion of this material (2.1 PgC) was retained over five years in the detrital carbon pool. A relatively small carbon accumulation also occurred in the forest products carbon pool.



Natural Siberian pine forest near Lake Baikal. Photo: M.Harmon.

Implementation of forest management measures within Russia can increase the future level of carbon storage in forest ecosystems by 2.02 PgC or by 2.8% (Table 3). Forest plantations and fire control appear to be the most promising measures, adding to the forest carbon pool 0.78 and 0.48 PgC, respectively. Other promising measures include extended harvest rotation due to reduced timber harvest (0.42 PgC) and stand improvement by silvicultural measures (0.35 PgC).

DISCUSSION

The variation in published estimates of carbon pools (Table 1) results from the diversity of estimation methods used. The lowest estimate comes from the study by Alexeev and Birdsey (14) which relies mainly on forest inventory data. The study that produced the highest biomass estimate as well as the highest net carbon accumulation value used mostly plot data and vegetation maps with some adjustments to reflect forest age-class composition (2). Such vegetation maps were widely used in the past and have been shown to overestimate live biomass stores (25).

Changes in carbon pools are the net result of continuous biomass dynamics in undisturbed stands over an entire forest area, as well as disturbances that occur on a small proportion of the forest area yet cause major changes in the affected forest car-

Table 3. Forest management options for conserving and sequestering carbon in the Russian forest sector.

Management option	Available land area (24) mill. ha	Additional MCS MgC ha^{-1}	Carbon sequestration potential, PgC
	(1)	(2)	(1 x 2)
Plantations on forest and agricultural lands	19.5	36.0	0.70
Plantations on other land categories (e.g., sands, drained peat bogs, mine tailings)	4.1	18.0	0.07
Increasing stand productivity with silvicultural measures	96.8	3.6	0.35
Reduction of stand replacement fires	13.3	36.0	0.48
Harvest reduction/ increased rotation	96.8	4.3	0.42
Total			2.02

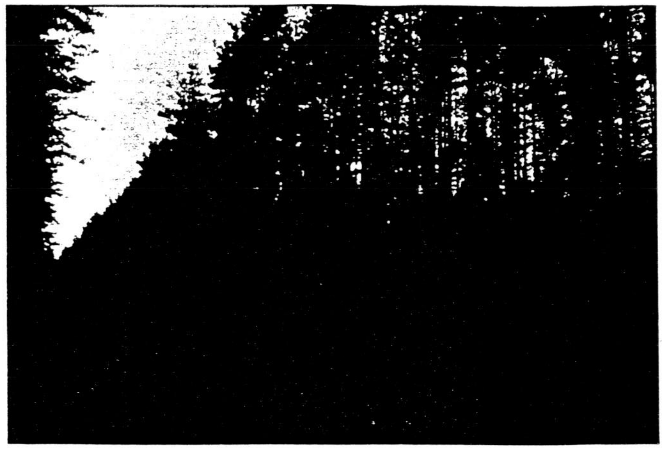
bon pools (26). The reduction in live biomass carbon stores between 1988 and 1993 in Russia indicates that over this 5-year period live biomass losses to fires, other natural disturbances, and timber harvest exceeded carbon accumulation in the growing trees. This time period includes two extreme fire years, 1989 and 1990, when forest fires were reported on a total of 3.6 mill. ha (the actual extent was probably much greater) (27). Other factors caused reported forest dieback on 0.2 mill. ha in 1991 alone (28). Forest harvests of 389 m^3 of wood accounted for a significant share of the live biomass loss (19). Harvesting has been a major factor in reducing the mature and overmature forest area that was reported in the forest inventory data since 1966 (29).

Only a small portion of the biomass carbon pool in a disturbed forest is instantly released into the atmosphere. The greater part of it is transferred into the detrital pool, while some is accumulated in forest products. These components are poorly studied and often ignored in carbon budget analyses (6). The lack of data on these key components inevitably leads to large uncertainties in carbon flux estimates (24, 30). This analysis of carbon dynamics from 1988 to 1993 suggests that carbon pools in both detritus and forest products were expanding and functioning as carbon sinks, while the live biomass pool was shrinking. This may be a common tendency in boreal forest zones as it was reported for Canada as well. For example, between 1970 and 1990, live biomass in Canadian forests decreased by 1.7 PgC, while the detrital pool and soils gained 3.1 PgC (3). Conversely, the live biomass of temperate forests was reported to increase (31–33). This may be attributed to a different history of forest resource development in temperate and boreal forests. For example, the expansion of the biomass pool in temperate forests may be reflecting regrowth after a long period of intensive harvesting while in the boreal zone the harvest, is still expanding into natural forests thereby reducing their carbon storage.

The carbon status of boreal forests that are not directly affected by land-use change and forestry practices may not be in steady-state as earlier assumed (34). Carbon dynamics fluctuate on a time scale of decades due to the variation in the level of natural disturbances that shape the forest age-class structure that largely determines the carbon balance (3). For example, following extreme fire years, insect outbreaks, and weather events, significant transfers of live biomass into the detrital pool, followed by a pulse of carbon release to the atmosphere, can be expected.

The rate of carbon release by woody detritus remains the biggest unknown in carbon budget calculations. In the carbon budgets reviewed, woody detritus was either ignored (15) or at best estimated as a constant proportion relative to the live biomass and presumed to be in equilibrium (2, 4). However, the share of dead wood within the total forest-stand biomass varies dramatically (from 2 to 98%) depending on disturbance and management practices. The use of a single expansion factor across successive stages may substantially over- or under-estimate the dead wood carbon pool, depending upon the disturbance regime of the area (20). In this study, a 3.3% annual decomposition rate was used based on measurements in northwestern Russia; for other regions this parameter was not available. Furthermore, this analysis indicates that, recently, the detrital pool was expanding, underscoring that the equilibrium assumption may not be valid.

A number of recent developments in the Russian forest sector may affect its carbon balance in the future. Harvest levels have decreased dramatically over the last few years due to an overall crisis in the Russian economy (35). This may contribute to carbon conservation for a short period of time, but the pressures of domestic and international timber markets will eventually restore and perhaps even increase harvest levels. Long-term efforts of forest managers in Russia to suppress forest fires to the extent possible (36) may result in a buildup of dead organic matter leading to catastrophic forest fires in the future. Such fires

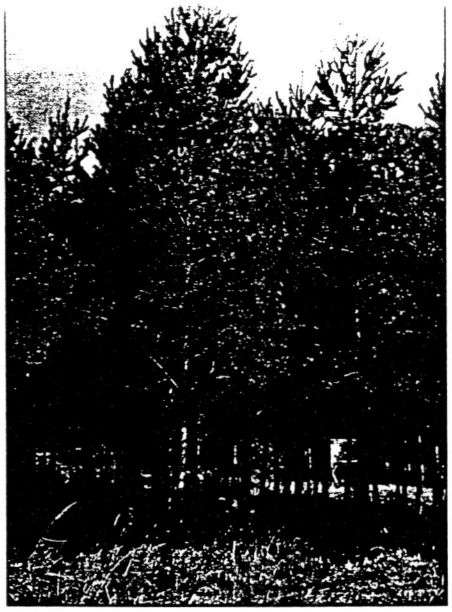


Mature Scots pine forest near St. Petersburg, Russia. Photo: J. Walstad.

could generate a large carbon flux to the atmosphere. Even greater fire-related carbon release can be expected as projected climate change accelerates vegetation dieback (37). According to climate change scenarios, forest vegetation in Russia may change on 334–631 mill. ha and generate a direct carbon flux to the atmosphere of 6.1–10.7 PgC (27). Forest dieback due to other factors (e.g., pests and pathogens, animal damage, weather extremes) is also likely to be exacerbated by changes in climate. Currently, an estimated 600–700 thousand ha in central Siberia are affected by an ongoing Siberian gypsy moth (*Dendrolimus sibiricus*) outbreak, the worst since the 1950s (38). In the next few years these affected forests are likely to be destroyed by fire. All these disturbances can further increase accumulation of greenhouse gases in the atmosphere and provide a positive feedback to global climate change.

Increasing use of forest resources by humans also significantly changes carbon dynamics of forest ecosystems. While it has been evident for some time that forest clearing for agriculture adds carbon to the atmosphere (39–41), there is considerable uncertainty regarding the effect of many common forest-management practices on carbon pools and fluxes. These practices were developed for purposes other than carbon storage and sequestration and they need to be evaluated with regard to carbon cycling. Conversion of older forest to younger forest has generally been shown to release carbon to the atmosphere (42–45). A complex of the current intensive management practices was shown to reduce carbon storage in forest ecosystems to 10–25% of the potential level found in undisturbed old-growth forest (24).The net effect of forest management practices upon atmospheric carbon fluxes depends upon: the ecosystem type; the types of pools considered (live only versus total ecosystem versus forest products); the initial starting conditions (old-growth forest versus bare ground); the type of silvicultural system used, and the fate of the harvested carbon (22). Preserving carbon stores, increasing sinks, and minimizing sources associated with forests have been the focus of evolving management strategies aimed at mitigating greenhouse gas accumulation in the atmosphere (4, 23, 46).

Russian forests have significant potential to be managed for the purposes of carbon sequestration because their carbon loading is far below the potential level. Forest plantations on 23.6 mill. ha of land currently without tree cover and capable of supporting productive forests can expand the area of closed forest by 3% and significantly increase carbon storage (Table 3), However, due to slow growth rates in boreal forests, the maximum carbon sequestration rate can be expected only 30–50 years following planting. Delayed carbon benefit also occurs in the case of silvicultural measures. A complex of measures aimed at averting catastrophic stand-replacement fires on large areas may in-



Scots pine plantations on a productive site near St. Petersburg, Russia. Photo: J. Walstad.

clude fire monitoring, prescribed burning, expanding areas of fire-resistant species, and maintaining the system of fire breaks. Unlike forest plantations and silvicultural practices, fire management and harvest reduction give instant results as they prevent carbon release rather than creating additional carbon sinks. If all the proposed measures are implemented, Russian forests can increase their current carbon storage by 2.02 Pg on a sustainable basis, a 2.8% increase over the current level or an equivalent of Russia's net carbon emissions over a period of three years (47). The potential for this additional carbon storage as estimated in this analysis is conservative because it does not include carbon accumulation in soil and forest products. Each option discussed provides multiple auxiliary benefits to the Russian national economy and local communities and represents a no-regret strategy for greenhouse gas mitigation.

References and Notes

1. Eriksson, H. 1992. Sources and sinks of carbon dioxide in Sweden. *Ambio 20*, 146–150.
2. Kolchugina, T.P., Vinson, T.S., Shwidenko, A.Z., Dixon, R.K., Kobak, K.I. and Botch, M.S. 1992. Carbon balance of forest biomes (undisturbed ecosystems) in the former Soviet Union. In: *Proceedings of the IPCC Workshop*. University of Joensuu, Finland, pp. 52–62.
3. Kurz, W.A., Apps, M.J., Beukema, S.J. and Lekstrum, T. Twentieth century carbon budget of Canadian forests. *Tellus*. (In press).
4. Krankina, O.N. and Dixon, R.K. 1994. Forest management options to conserve and sequester terrestrial carbon in the Russian Federation. *World Resource Review 6*, 88–101.
5. Turner, D.P. Koerper, G.J., Harmon, M.E. and Lee J.J. 1995. A carbon budget for forests of the conterminous United States. *Ecol. Applicat. 5*, 421–436.
6. Dixon, R. K., Brown, S., Houghton, R. A., Solomon, A. M., Trexler and M. C., Wisniewski, J. 1994. Carbon pools and flux of global forest ecosystems. *Science 263*, 185–190.
7. Houghton, R. A. and Skole, D. L. 1990. Changes in the global carbon cycle between 1700 and 1985. In: *The Earth Transformed by Human Action*. Turner, B. L. (ed.). Cambridge Univ. Press, NY, pp. 393–408.
8. World Resources Institute (WRI). 1990. *World Resources 1990-1991*. Oxford University Press, Oxford, UK, 383 pp.
9. Houghton, J.T., Callander, B.A. and Varney, S.K. (eds). 1992. *Climate Change, 1992, The Supplementary Report to the IPCC Scientific Assessment*. University Press, Cambridge, UK.
10. Rubin, E.S., Cooper, R.N., Frosch, R.A., Lee, T.H., Marland, G., Rosenfeld, A.J. and Stone, D.D. 1992. Realistic mitigation options for global warming. *Science 257*, 148–149, 261–266.
11. Anonymous. 1990. *Forest Fund of the USSR*. State Committee for Forestry, Moscow, Russia 1–2. (In Russian).
12. Krankina, O.N. and Dixon. R.K. 1992. Forest management in Russia: Challenges and opportunities in the era of perestroika. *J. For. 6*, 29–34.
13. Anuchin, N.P., et al. (Author, please give all authors). 1985. *Forest Encyclopedia*. Soviet Encyclopedia, Moscow, Russia 1–2 (In Russian).
14. Alexeev, V.A. and Birdsey, R.A. 1994. *Carbon in Ecosystems of Forests and Peatlands of Russia*. Ecos, Krasnoyarsk, Russia. (In Russian).
15. Isaev, A.S., Korovin, G.N., Utkin, A.I., Pryazhnikov, A.A. and Zamolodchikov, D.G. 1993. Estimation of carbon pool and its annual deposition in phytomass of forest ecosystems in Russia. *Lesovedenie 5*, 3–10 (In Russian).
16. Anonymous. 1995. *Forest Fund of Russia*. Russian Federal Forest Service, Moscow, Russia. (In Russian).
17. Bazilevich, N.I. 1993. *Biological Productivity of Ecosystems of Northern Eurasia*. Nauka Publishers, Moscow, Russia. (In Russian).
18. Kazimirov, N.I. and Morozova, R.M. 1973. *Biological Cycling of Matter in Spruce Forests of Karelia*. Nauka, Leningrad, Russia.
19. World Resources Institute (WRI). 1992. *World Resources 1992-1993*. Oxford University Press, New Oxford, UK, 383 pp.
20. Krankina O.N. and Harmon, M.E. 1995. Dynamics of the dead wood carbon pool in Northwestern Russian boreal forest. *Water Air Soil Pollut. 82*, 227–238.
21. Anonymous. *National Economy of the USSR*. 1991. Statistica, Moscow, Russia (In Russian).
22. Harmon, M.E., Harmon, J.M., Ferrell, W.K. and Brooks, D. Modelling carbon stores in Oregon and Washington forest products:1900–1992. *Climate Change*. (In review).
23. Winjum, J.K., Dixon, R.K. and Schroeder, P.E. 1993. Forest management and carbon storage: an analysis of 12 key forest nations. *Water Air Soil Pollut. 70*, 239–257.
24. Krankina O.N. and Harmon, M.E. 1994. The impact of intensive forest management on carbon stores in forest ecosystems. *World Resource Rev. 6*, 161–177.
25. Botkin, D.B. and Simpson, L.G. 1990. Biomass of the North American boreal forest—A step toward accurate global estimates. *Biogeochem. 9*, 161–174.
26. Kurz, W.A., Apps, M.J., Webb, T.M. and McNamee, P.J. 1992. *The Carbon Budget of the Canadian Forest Sector: Phase 1*. Forestry Canada. Information Report NOR-X-326. Edmonton, Alberta, 93 pp.
27. Dixon, R.K. and Krankina, O.N. 1993. Forest fires in Russia: carbon dioxide emissions to the atmosphere. *Can. J. For. Res. 23*, 700–705.
28. Krankina, O.N., Dixon, R.K., Shvidenko A.Z. and Selikhovkin, A.V. 1994. Forest dieback in Russia: causes, distribution and implications for the future. *World Resource Rev. 6*, 524–534.
29. Anonymous. 1989. *Dynamics of Forests under State Forest Management by Major Tree Species in 1966–1988*. State Committee for Forestry, Moscow, Russia. (In Russian).
30. Houghton, R.A. 1993. Is carbon accumulating in the northern temperate zone? *Global Biogeochem. Cycles 7*, 611–617.
31. Sedjo, R.A. 1992. Temperate forest ecosystems in the global carbon cycle. *Ambio 21*, 274–277.
32. Kauppi, P., Mielikainen, K. and Kuusela, K. 1992. Biomass and carbon budget of European forests, 1971–1990, *Science 256*, 70–74.
33. Musselman, R.C. and Fox, D.G. 1991. A review of the role of temperate forests in the global CO_2 balance. *J. Air Waste Mgmt Assoc. 41*, 798–807.
34. Houghton, R.A., Boone, R.D., Fruci, J.R., Hobbie, J.E., Melillo, J.M., Palm, C.A., Peterson, B.J., Shaver, G.R., Woodwell, G.M., Moore, B. and Skole, D.L. 1987. The flux of carbon from terrestrial ecosystems to the atmosphere in 1980 due to changes in land-use: geographical distribution of the global flux. *Tellus 39B*, 122–139.
35. Korovin, G.N. 1995. The problems of forest management of Russia. *Air Water Soil Pollut. 82*, 13–24.
36. Odintsov, D.I. 1991. Save forests from fire. *For. Mgmt 4*, 6–9. (In Russian).
37. King, G. and Neilson, R.P. 1992. The transient response of vegetation to climate change: a potential source of CO_2 to the atmosphere. *Water Air Soil Pollut. 64*, 365–383.
38. Tarasov, A. 1995. Biological fire in Siberian taiga. *Izvestia*, August 19. 2 pp. (In Russian).
39. Woodwell, G.M., Whittaker, R.H., Reiners, W.A., Likens, G.E., Delwiche, C.C. and Botkin, D.B. 1978. The biota and the world carbon budget. *Science 199*, 141–146.
40. Houghton, R. A. and Woodwell,G. M. 1989. Global climate change. *Sci. Am. 260*, 36–44.
41. Melillo, J.M., Fruci, J.R., Houghton, R.A., Moor III, B. and Skole D.L. 1988. Land-use change in the Soviet Union between 1850-1980; cause of a net release of CO_2 to the atmosphere. *Tellus 40*, 116–128.
42. Alaback, P.B. 1989. Logging of temperate rainforests and greenhouse effect: ecological factors to consider. In: *Proceedings of Watershed '89*. Alexander, E.B. (ed.). 195–202 pp.
43. Harmon, M. E., Ferrell, W. K. and Franklin, J. F. 1990. Effects on carbon storage of conversion of old-growth forests to young forests. *Science 247*, 699–702.
44. Dewar, R.C. 1991. Analytical model of carbon storage in the trees, soils, and wood products of managed forests. *Tree Physiology 8*, 239–258.
45. Kershaw, J.A., Oliver, C.D. and Hinckley, T.M. 1993. Effect of harvest of old-growth Douglas-fir stands and subsequent management on carbon dioxide levels in the atmosphere. *J. Sustain. For. 1*, 61–77.
46. Trexler, M.C. 1993. Manipulating biotic carbon sources and sinks for climate change mitigation: can science keep up with practice? *Water Air Soil Pollut. 70*, 579–593.
47. Kolchugina, T.P. and Vinson, T.S. 1994. Production of the greenhouse gases in the former Soviet Union. *World Resource Rev. 6*, 291–303.

48. The senior author would like to thank Lawrence Berkeley National Laboratory and the US Country Studies Program for the invitation to participate in the Regional Workshop on Greenhouse Gas Emissions Inventory and Mitigation Strategies for Asian and Pacific Countries. Her participation in the Workshop prompted the writing of this paper.

Dr. Olga N. Krankina received her PhD in forest management from St. Petersburg Forest Academy, Russia, 1986. Since 1991, she has worked at Oregon State University where her primary areas of interest are the ecology of boreal forests, carbon cycling, tree mortality, and decomposition of woody detritus. Her address: Department of Forest Science, Oregon State University, Corvallis, Oregon 97331, USA.

Dr. Jack K. Wijum received his PhD in forest ecology from the University of Michigan in 1968. His most recent field of research interest is the role of forest management and agroforestry systems as mitigative and adaptive measures in global environmental change. His address: National Council for Air and Stream Improvement (NCASI), U.S. EPA National Health and Environmental Effects Research Laboratory, Western Ecology Division, 200 SW 35th St. Corvallis, Oregon 97333, USA.

Dr. Mark E. Harmon received his PhD in botany from Oregon State University in 1986. His research interests include ecosystem succession processes, decomposition, nutrient cycling, and carbon dynamics.His address: Department of Forest Science, Oregon State University, Corvallis, Oregon 97331, USA.