A large carbon sink in the woody biomass of Northern forests

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The terrestrial carbon sink, as of yet unidentified, represents 15–30% of annual global emissions of carbon from fossil fuels and industrial activities. Some of the missing carbon is sequestered in vegetation biomass and, under the Kyoto Protocol of the United Nations Framework Convention on Climate Change, industrialized nations can use certain forest biomass sinks to meet their greenhouse gas emissions reduction commitments. Therefore, we analyzed 19 years of data from remote-sensing spacecraft and forest inventories to identify the size and location of such sinks. The results, which cover the years 1981–1999, reveal a picture of biomass carbon gains in Eurasian boreal and North American temperate forests and losses in some Canadian boreal forests. For the 1.42 billion hectares of Northern forests, roughly above the 30th parallel, we estimate the biomass sink to be 0.68 ± 0.34 billion tons carbon per year, of which nearly 70% is in Eurasia, in proportion to its forest area and in disproportion to its biomass carbon pool. The relatively high spatial resolution of these estimates permits direct validation with ground data and contributes to a monitoring program of forest biomass sinks under the Kyoto protocol.

Carbon on land is contained in various pools such as vegetation, detritus, soil, black carbon residue from fires, harvested products, etc. (1). About 1–2 giga tons (Gt) (10^9) of carbon a year are suggested to be somehow sequestered in pools on land in the temperate and boreal regions (2, 3). These sinks represent 15–30% of annual global emissions of carbon from fossil fuels and industrial activities. The use of carbon sinks in policies governing reductions in greenhouse gas emissions presently is being debated (4). Thus, characterizing the location and mechanism of carbon sinks is of scientific and political importance.

This study is limited to analysis of the carbon pool in the woody biomass of temperate and boreal forests of the Northern Hemisphere, which cover an area of about 1.4–1.5 billion hectares (ha) (5). We define forests as the following remote sensing land covers (6): broad leaf forests, needle leaf forests, mixed forests, and woody savannas. This land cover definition is broadly consistent with land use definitions of a forest (4), but not of forest and other wooded land used by the Food and Agriculture Organization (5). Woody biomass consists of wood, bark, branches, twigs, stumps and roots of live trees, shrubs, and bushes. The vegetation pool gains carbon from productivity investment in these components and loses carbon because of aging, mortality, harvest, fire, disease, insect attacks, wind throw, etc.

Satellite observations of vegetation have provided global coverage with relatively high spatial resolution and consistent time coverage since the early 1980s. Forest biomass cannot be directly measured from space yet, but, as we demonstrate below, remotely sensed greenness can be used as an effective surrogate for biomass on decadal and longer time scales in regions of distinct seasonality, as in the north. Year-to-year changes in biomass are quite small, about 2 orders of magnitude smaller than the biomass pool. At decadal and longer time scales, the biomass changes can be considerable because of accrual of differences between gains and losses. Potentially, these can be observed as low-frequency variations in greenness, in much the same way as greenness changes at century and longer time scales are suggestive of successional changes.

Data and Method

We processed about 40,000 orbits of daily data from the advanced very high-resolution radiometers on board the National Oceanic and Atmospheric Administration series satellites 7, 9, 11, and 14 to produce a global 15-day normalized difference vegetation index (NDVI) data set at 8-km resolution (pixel area is 64 km^2) from July 1981 to December 1999. The NDVI data capture the contrast between red and near-IR reflection of solar radiation by vegetation that is indicative of the amount of green leaf area (7). The NDVI is expressed on a scale between -1 and $+1$ and increases from about 0.1 to 0.75 for progressively increasing amounts of vegetation, but saturates in the case of dense leaf canopies, for example, the humid tropical forests and old growth forests. In regions of distinct seasonality, as in the north, the cumulative growing season NDVI succinctly captures both the average seasonal level of greenness and the growing season duration and is therefore an ideal measure of seasonal vegetation greenness.

The processing of satellite data involved cloud screening and calibration for sensor degradation and intersensor variations. Residual atmospheric effects were minimized by analyzing only the maximum NDVI value within each 15-day interval. These data generally correspond to observations from near-nadir viewing directions and clear atmospheric conditions. The data from April 1982 to December 1984 and from June 1991 to December 1993 were corrected to remove the effects of stratospheric aerosol loadings from El Chichon and Mount Pinatubo eruptions on the NDVI data. Details on development of the NDVI data set and an evaluation of its quality can be found in Zhou *et al.* (8). This third-generation data set overcomes most problems noted in previous generations of NDVI data sets (7–9).

We analyzed 1980s and 1990s inventory data of stem wood volume from 171 provinces in six countries (Canada, Finland, Norway, Russia, Sweden, and United States) covering more than one billion ha of northern temperate and boreal forests.

Abbreviations: NDVI, normalized difference vegetation index; Gt, giga tons; Mt, million tons; ha, hectare; Mha, million ha; TBFRA, Temperate and Boreal Forest Resources Assessment.

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The inventory data were converted to above-stump and total biomass by using country-specific coefficients (5). To match these to NDVI data, the distribution of forest area in each province is required, because the NDVI data are pixel data. Therefore, we used a 1 × 1-km remote sensing land cover map (6). For each province, in a geographical information system, we evaluated the cumulative growing season greenness from NDVI data layers by averaging over forest pixels as identified from the land cover map. This procedure assured that the resulting provincial NDVI totals were assembled from forested regions only. These were then averaged over the inventory period, typically about 5 years. Part A of the supporting information, which is published on the PNAS web site, www.pnas.org, provides the list of provinces, forest distribution by area, genus and age, formulas for evaluating biomass from wood volume data, and the methodology used for matching inventory and remote sensing data. For a discussion on the merits and limitations of the inventory method for estimation of biomass stocks, the reader is referred to chapter 2 in ref. 4.

Results

The relation between inventory estimates of woody biomass and remote sensing estimates of seasonal greenness is shown in Fig. 1. Data from the United States are displayed to distinguish states with predominant needle leaf presence from those with broad leaf forests. The outliers represent high biomass, old growth forests of the Pacific northwestern states—British Columbia in Canada; Washington, Oregon and (northern) California in the United States—situations where the satellite NDVI data saturate, as discussed in *Data and Method*. For the rest, Fig. 1 suggests a relation between biomass and satellite greenness data, which is remarkable given the wide variety of inventory practices, provincial forest areas, ecosystem types, age structures, fire and insect dynamics, management practices, and time periods.

The data shown in Fig. 1 (without the outliers) are transformed (compare Fig. 1 legend) and used to estimate a statistically significant relation between biomass and seasonal greenness totals. The results indicate that biomass increases with NDVI and varies with latitude, with the largest values in temperate latitudes. The ability of this equation to represent the relation between biomass and NDVI across spatial, temporal, and ecological scales was evaluated by testing the null hypothesis that the regression coefficients do not vary among nations, time periods, NDVI, or latitude. The results indicate that the coefficient associated with NDVI is stable across a large portion of the observed range for NDVI, latitude, and among nations. Thus, the regression model obtained from pooled data were used to generate all biomass estimates discussed below. We also ran a Monte Carlo simulation to estimate uncertainty in the sink estimate generated by this relation. The results indicate that the standard error of the per-pixel biomass change is 1 or 2 orders of magnitude smaller than the average change of 0.48 tons C/ha per year. Thus, it is highly unlikely that the carbon sink estimates given below are a statistical artifact of uncertainty regarding the relation between biomass and NDVI. Part B of the supporting information, which is published on the PNAS web site, provides the details.

Because of their high spatial resolution, relative to province inventory measurements, biomass estimates from satellite data provide spatial detail of the carbon pool and where changes in the pool have occurred. To document these regional features, we show, in Fig. 2, a color coded map of biomass changes between the late 1990s (1995–1999) and early 1980s (1982–1986), together with a map of the carbon pool during late 1990s (1995–1999), both evaluated from pixel-level NDVI data with the regression model discussed above.

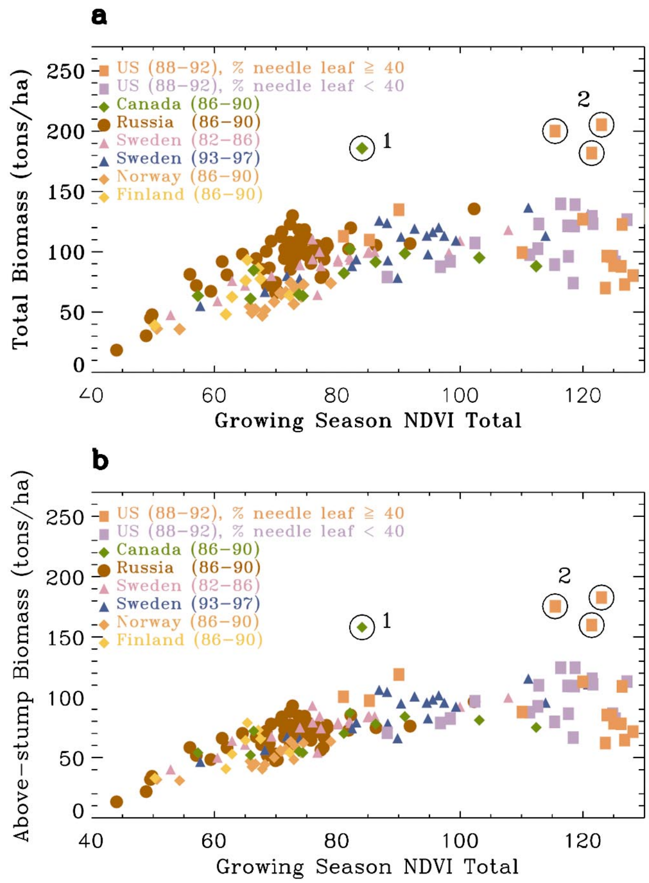

Fig. 1. Plot of total (*a*) and above-stump (*b*) woody biomass versus cumulative growing season NDVI. The growing season is defined as the period when NDVI is greater than 0.1 because values below this threshold tend to be associated with marginally vegetated regions, senescing vegetation, and bare soils. Data from 171 of the 205 provinces (Sweden twice), where forest area is greater than 15% of the land area, are shown. The wood volume data sources from which biomass was computed are inventory yearbooks (Finland, Norway, and Sweden) and reports (10–12). Outlier 1 is British Columbia (Canada) and outliers 2 are data from Washington, Oregon, and (northern) California. These represent 16% of North American forest area. The data, without the outliers, were regressed to obtain a statistically significant relation between biomass and greenness levels by using the following specification: $(1/y) = a + b*\text{Lat} + c*[(1/x)/\text{Lat}^2] + e$, where Lat is latitude of the inventory province centroid (degrees), x is growing season NDVI total, averaged over the 5-year inventory period, and y is either above-stump or total woody biomass per ha of the province, e is a normally distributed random error, and a, b, and c are regression coefficients. The value of these coefficients is estimated by using ordinary least squares. For total biomass, $a = -0.0377$ (± 0.00977), $b = 0.0006$ (± 0.00011), $c = 3809.65$ (± 902.51); adjusted $r^2 = 0.43$. For above-stump biomass, $a = -0.0557$ (± 0.0136), $b = 0.000854$ (± 0.000153), $c = 5548.05$ (± 1274.17); adjusted $r^2 = 0.49$. Values in parentheses are standard errors. Using t tests, we reject the null hypothesis that the individual regression coefficients are equal to zero ($P < 0.001$).

The spatial picture of changes in the biomass pool, shown in Fig. 2*a*, depicts carbon gains, in excess of 0.3 tons of C/ha per year, in Eurasian boreal and North American temperate forests, and carbon losses, greater than 0.1 tons C/ha per year, in some Canadian boreal forests. The gains are observed in Eurasia over a large, broad, nearly contiguous swath of land, from Sweden (about 10°E, north of 60°N), through Finland, European Russia, central Siberia to trans-Baikalia (120°E, north of 50°N). In North America, similarly large gains are seen in the eastern temperate forests of the United States and

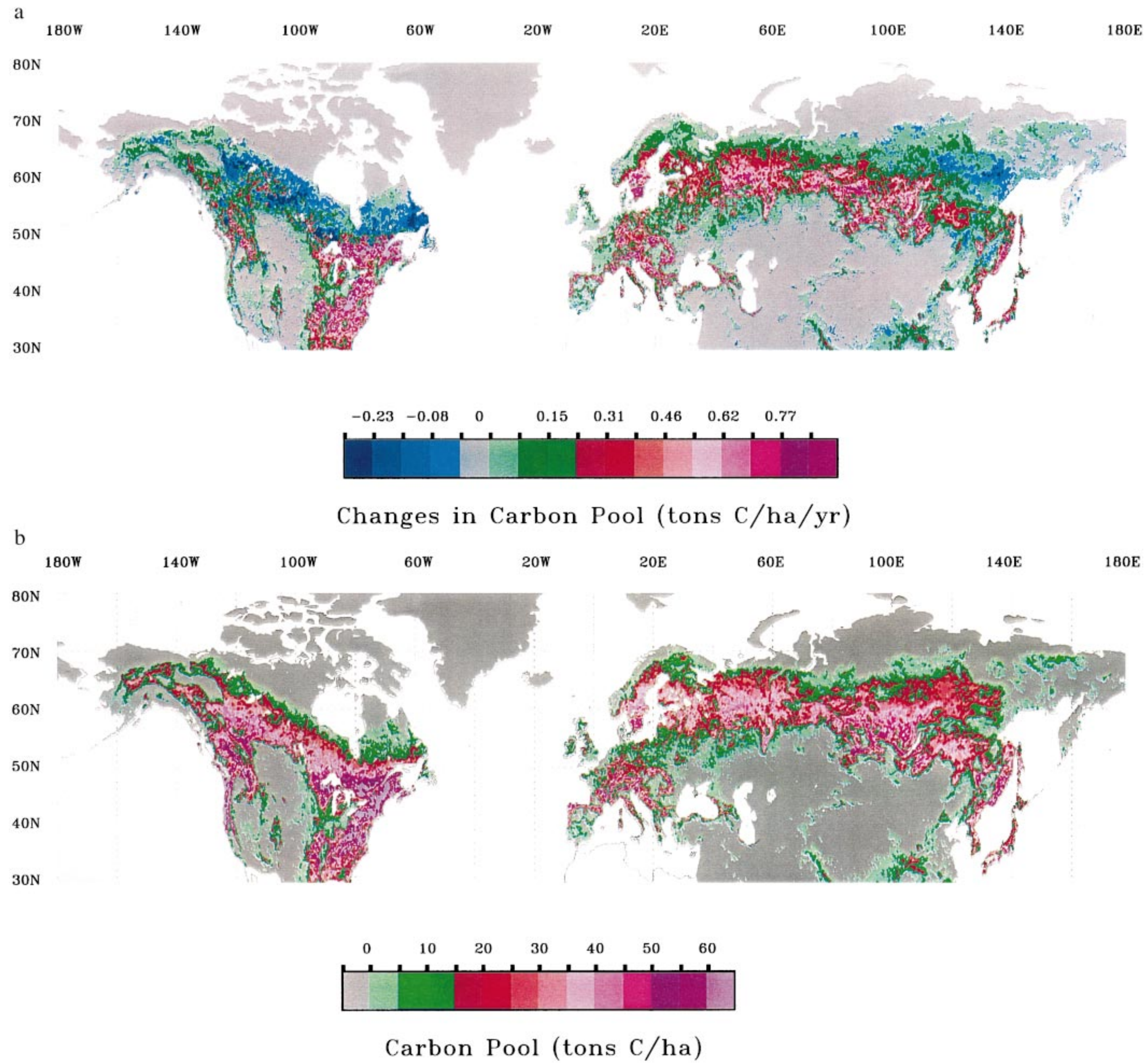

Fig. 2. Spatial detail of changes in the woody biomass carbon pool of northern temperate and boreal forests between late 1990s and early 1980s (*a*) and pool size during late 1990s (*b*). Biomass estimates were converted to carbon by multiplying by 0.5, a standard factor for converting woody biomass to carbon (4, 5).

in southern Ontario and Quebec below the 50th parallel. Carbon losses are seen in Canada's boreal forests, from Newfoundland to the Northwest territories, except in smaller fragments in northern Saskatchewan and Alberta, where gains are observed (about 110°W and 60°N). Part C of the supporting information, which is published on the PNAS web site, provides detailed maps of biomass carbon changes together with maps of forest density and NDVI changes from which these results were generated.

The biomass map shown in Fig. 2*b* indicates larger average pools, in tons C/ha, in North America compared with Eurasia (51 vs. 39). The average pool size in Europe and the United States is larger than in Canada and Russia (54–58 vs. 38–44). Among the European countries, Austria, France, and Germany have notably large average pools (60, 67 and 73, respectively). The estimates for Finland, Norway, and Sweden are comparable to Russia (35–40 vs. 38).

Uncertainties in our estimates of biomass pool and changes were evaluated by comparing these to national, provincial and state estimates (Fig. 3). The average absolute difference between remote sensing and these inventory estimates is 10.4 tons C/ha for above-stump biomass, 16.1 tons C/ha for total biomass, and 0.33 tons C/ha per year for changes in pool size, or 27%, 33%, and 50% of the mean inventory estimates, respectively. There is no bias in the estimation of biomass pools and changes to the pools (part D.3 of the supporting information). The national inventory sink estimates (5), in Fig. 3*b*, were derived from wood volume increment and loss data (natural and fellings), unlike remote sensing estimates which are biomass differences between two time periods. The comparability of the two estimates is thus noteworthy.

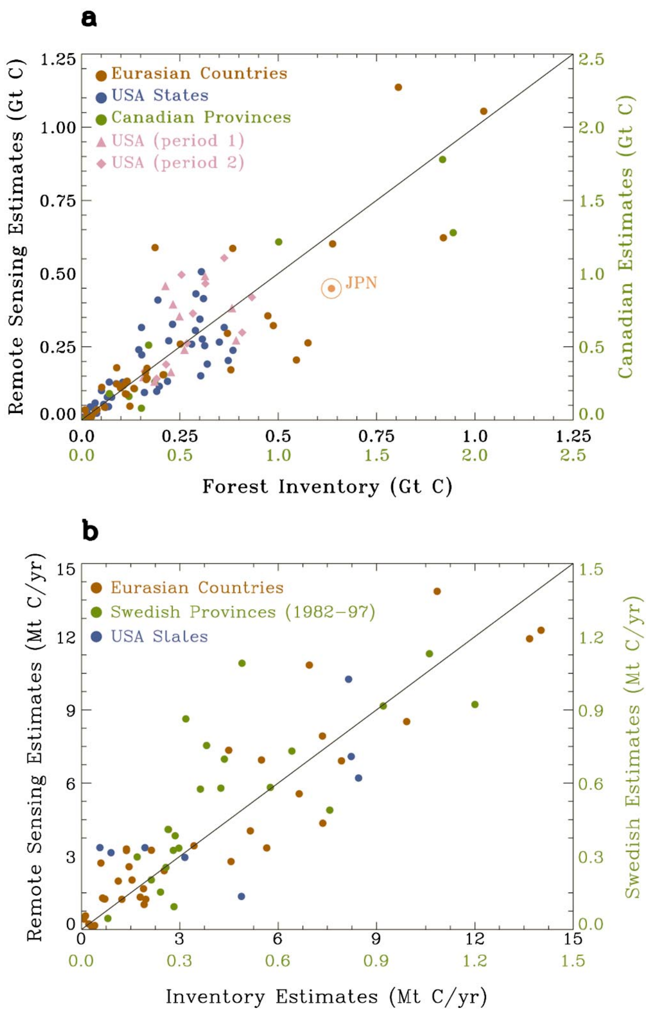

Fig. 3. Comparison of remote sensing and inventory estimates of the biomass carbon pool and its rate of change. We show estimates at the provincial, state, and national level, rather than on per-unit forest area basis, to include uncertainties associated with differences in respective estimates of forest area. (*a*) Estimates of above-stump biomass carbon pool in 46 states of the United States (13), 11 provinces of Canada (14), and total biomass pool in 37 Eurasian countries (5). Also shown are inventory biomass estimates for 10 states of the United States for which data are available for two time periods (www.srsfia.usfs.msstate.edu/scripts/ew.htm). The remote sensing estimates were obtained with the regression model from pixel-level growing season NDVI total, averaged over the inventory period, together with a high-resolution satellite vegetation map (6). The inventory estimates shown here were not used in the development of the regression equation. Estimates for Japan were divided by 2 to correspond with the axes. (*b*) Changes in the biomass carbon pool in 22 provinces of Sweden, nine states of the United States (www.srsfia.usfs.msstate.edu/scripts/ew.htm) and 37 Eurasian countries (5). The Swedish data are changes recorded in two successive inventories (1993–1997 and 1982–1986) of stem wood volume converted to woody biomass in carbon units and divided by the time interval (11 years). Likewise, the data are shown for the nine states of the United States. The Eurasian data are for the early to mid-1990s. Only the Swedish data were used in the development of the regression model. The remote sensing estimates are differences in the predicted carbon pool for the respective time periods and expressed on an annual basis. Part D of the supporting information, which is published on the PNAS web site, provides a list of provinces, states, and countries shown here.

We estimate the carbon pool in the woody biomass of 1,420 million hectares (Mha) of temperate and boreal forests in the Northern Hemisphere to be 61 ± 20 Gt C during the late 1990s (Table 1). This finding is comparable to the Temperate and Boreal Forest Resources Assessment (TBFRA)-2000 (5), which reports a carbon pool of 80 Gt C, but on 2,477 Mha of forests and other wooded land. Both of these estimates are considerably lower than the estimate, 147 Gt C on 2,410 Mha of forests and other wooded land, quoted by the Intergovernmental Panel on Climate Change (4). Earlier studies may have overestimated carbon pools possibly because of unrepresentative samples, which tend to bias toward sites with larger than average pools (15). If this has occurred for tropical forests and savannas, the current estimate of global vegetation carbon pool, 466 Gt C, may also be too large (4).

Our estimate for the woody biomass sink during the 1980s and 1990s is 0.68 ± 0.34 Gt C/year. This is in the midrange of estimates by Sedjo (16) for mid-1980s (0.36 Gt C/year) and TBFRA-2000 (5) for early and mid-1990s (0.81 Gt C/year). The remote sensing and TBFRA-2000 sink estimates are ≈1% of the biomass pool (Sedjo did not report the pool size). Estimates of forest area, biomass pool and sink by country are given in part E of the supporting information, which is published on the PNAS web site.

It is instructive to compare the sink estimates of North America and Eurasia in view of a large terrestrial North American sink and weak Eurasian sink reported for the 1988–1992 time period (17). The average sequestration rate, in tons C/ha per year, is highest in Europe (0.84) and the United States (0.66), and least in Canada and China (0.27–0.31), with values for Russia in between (0.44). Consequently, the average sequestration rate is comparable between North America and Eurasia (0.47–0.49), unlike the average pool sizes (51 vs. 39 tons C/ha). Thus, nearly 70% of the biomass sink is in Eurasia (0.47 Gt C/year), in proportion to its forest area and in disproportion to its pool size (Table 1).

The estimates of the three large countries (Canada, Russia, and the United States) are crucial to overall accuracy because they account for 78% of the pool, 73% of the sink, and 77% of the forest area (Table 2). Our pool, sink, and forest area estimates for Canada and the United States are comparable to TBFRA-2000 (5). Our sink estimate for the United States (0.142 Gt C/year) is comparable to most estimates for the 1980s (0.02–0.15 Gt C/year) (18–21). The losses observed in some Canadian boreal forests (Fig. 2*a*) are consistent with reports of disturbances from fires and insects during the 1980s and 1990s (22). For the entire country, however, we estimate a sink of about 0.073 Gt C/year, which is comparable to an inventory estimate by the Canadian Forest Service (0.091 Gt C/year) for 1982–1991 (23).

Estimates for Russia are especially crucial and they tend to differ (Table 2). The remote sensing estimate of forest area, 642 Mha, is about 130–180 Mha lower, possibly because of the resolution of satellite data, which may be too coarse for detecting tree stands in the forest-tundra of Russia, where small lots of sparse stands with extremely low growing stock are distributed among the vast peatlands. But, when expressed on per-ha forest area basis, the various pool estimates are comparable (38–43 tons C/ha). The difference in sink estimates between remote sensing and TBFRA-2000 is smaller (0.44 vs. 0.53; in tons C/ha per year). Nilsson *et al.*'s (24) sink estimate, 0.058 Gt C/year, is significantly lower than our (0.292 Gt C/year) and TBFRA-2000 estimates (0.423 Gt C/year). These differences are likely caused by different methods for estimating the sink. Part F of the supporting information, which is published on the PNAS web site, provides further details.

Discussion

The reasons for the observed changes are not known but the spatial patterns seen in Fig. 2*a* offer some clues. Increased incidence of fires and infestations in Canada, fire suppression and forest regrowth in the United States, declining harvests in

Table 1. Remote sensing estimates of carbon pool (1995–1999) and sink in the woody biomass of temperate and boreal forests in North America and Eurasia

Country	Average pool, tons/ha	Carbon pool, Gt C	Carbon sink, Gt C/yr	Forest area, Mha
Canada	44.09	10.56	0.07312	239.5
United States	57.91	12.48	0.14153	215.5
North America	50.64	23.04	0.21465	455.0
China	25.77	3.68	0.03862	142.6
Finland	34.88	0.60	0.00556	17.2
Japan	47.35	0.90	0.01192	19.0
Russia	37.98	24.39	0.28359	642.2
Sweden	39.86	1.06	0.01386	26.5
Other*	59.40	7.05	0.11617	117.4
Eurasia	39.99	37.68	0.46972	964.9
Total	42.91	60.72	0.68437	1,419.9

*Albania, Armenia, Austria, Azerbaijan, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, France, Georgia, Germany, Greece, Hungary, Italy, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Switzerland, Tajikistan, Turkey, Turkmenistan, United Kingdom, Ukraine, Uzbekistan.

Russia, improved silviculture in the Nordic countries, and woody encroachment and longer growing seasons from warming in the northern latitudes possibly explain some of the changes (18, 22, 25–29). This implies uncertainty regarding the future of biomass sinks and therefore the need for monitoring.

How robust are these results? Residual atmospheric effects and calibration errors in satellite data cannot be ruled out. Uncertainties in inventory data are country-specific and difficult to quantify (5). Simple models are used to convert wood volume and greenness data to biomass. The differences in forest area estimates between remote sensing and inventories are not easy to reconcile because of definition issues. All of this suggests a cautionary reading of the results and need for further research.

This work contributes to global carbon cycle research in four ways. First, it provides spatial detail of the biomass carbon pool and where changes in this pool have occurred at a resolution that permits direct validation with ground data. Second, the NDVI data, when used in inversion studies, provide additional constraints to inferences of source/sink distribution from atmospheric CO_2 and isotopic concentration data. Third, the inversion studies cannot partition the inferred sink between vegetation, soil, and other pools. For example, if the vegetation is a sink and the soil is a source, estimates of vegetation pool changes would complement inversion results.

Finally, debate is currently under way regarding which of the forest biomass sinks can be used by the Annex 1 parties, the industrialized nations, to meet their greenhouse gas emissions reduction commitments under the Kyoto Protocol of the United Nations Framework Convention on Climate Change. Satellite estimates of biomass changes can be an important component of carbon accounting (4, 24) for verification of compliance, if the uncertainty of these estimates can be further reduced. Improved observations of greenness levels from a new generation of spacecraft sensors such as the moderate-resolution imaging spectroradiometer and multiangle imaging spectroradiometer (30), and possibly direct biomass measurements with lidars, offer promise for the future.

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Table 2. Comparison of estimates for Canada, Russia, and the United States

	Remote sensing estimates			Inventory and other estimates		
Country	Pool, Gt C	Sink, Gt C/yr	Area, Mha	Pool, Gt C	Sink, Gt C/yr	Area, Mha
Canada	10.56	0.0731	239.5	11.89[a]	0.093[a]	244.6[a]
					0.085[b]	
Russia	24.39	0.2836	642.2	32.86[c]	0.429[a]	816.5[a]
					0.058[c]	763.5[c]
						770.8[d]
United States	12.48	0.1415	215.5	13.85[a]	0.167[a]	
					0.063[e]	
					0.098[f]	217.3[a]
					0.020[g]	247.0[h]
					0.11–0.15[h]	

[a]TBFRA-2000 (5); estimates for early to mid-1990s.
[b]From inventory data (23); for 1982–1991.
[c]Nilsson *et al.* (24); for 1990.
[d]Alexyev and Birdsey (11); for 1990.
[e]Turner *et al.* (19); for the 1980s.
[f]Birdsey and Heath (20); for the 1980s.
[g]Houghton *et al.* (18); for the 1980s; land-use study.
[h]Pacala *et al.* (21); for 1980–1990; forest trees in coterminous United States only.

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