CARBON STORES, SINKS, AND SOURCES IN FORESTS OF NORTHWESTERN RUSSIA: CAN WE RECONCILE FOREST INVENTORIES WITH REMOTE SENSING RESULTS?

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Abstract. Forest inventories and remote sensing are the two principal data sources used to estimate carbon (C) stocks and fluxes for large forest regions. National governments have historically relied on forest inventories for assessments but developments in remote sensing technology provide additional opportunities for operational C monitoring. The estimate of total C stock in live forest biomass modeled from Landsat imagery for the St. Petersburg region was consistent with estimates derived from forest inventory data for the early 1990s (272 and 269 TgC, respectively). The estimates of mean C sink in live forest biomass also agreed well (0.36 and 0.34 Mg C ha^{-1} yr^{-1}). Virtually all forest lands were accumulating C in live biomass, however when the net change in total ecosystem C stock was considered, 19% of the forest area were a net source of C. The average net C sink in total ecosystem biomass is quite weak (0.08 MgC ha^{-1} yr^{-1} and could be reversed by minor increases in harvest rates or a small decline in biomass growth rates.

1. Introduction

The challenge of balancing the global carbon (C) budget and understanding the role of terrestrial ecosystems has remained a central issue of scientific research for decades (e.g. Schimel et al., 2001). However, the needs of reporting C stocks and stock changes for the Kyoto Protocol's first commitment period (2008–2012) and the emerging field of C trading have put additional demands on methods for estimating C sources and sinks. The need for accurate estimates that are verifiable, specific in time and space, and cover large areas at acceptable cost cannot be fully met at present by any existing operational system. However, these systems can be used as a basis for the development of new integrative methods designed to meet these newly emerging requirements. Forest inventories and remote sensing are the two principal data sources used to estimate C stocks and flux for large forest regions. National governments have historically relied on forest inventories to estimate C stocks, sources, and sinks on their forestlands but developments in remote sensing technology provide additional opportunities for operational C

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monitoring from space. In many countries efforts are underway to use remote sensing within national forest inventory systems, and samples of forest inventory data are used to interpret remotely sensed data (Krankina et al., 1998). However, to date these two data sources remain largely independent. Neither data source can provide a direct measurement of C store or flux, in both cases these variables have to be estimated or modeled in some way. Usually, some combination of allometric equations and regression modeling is used to estimate biomass stocks, those are converted to C, and C flux (sink or source) is estimated as change in C stocks over time. Because there are countless ways of doing this, the estimates of C stocks and flux are often different and difficult to reconcile.

Yet another approach relies on remote sensing to derive leaf area index, NDVI, or other parameters from remote sensing and then uses them in process-based simulation models (e.g., Running et al., 2000; Schimel et al., 2001). These models are widely used to examine the effects of seasonal and inter-annual variation in C exchange, but the inability to predict the net change in total ecosystem C stocks over timescale of years to decades limits the utility of these models in the context of Kyoto Protocol and other efforts at monitoring C stocks in terrestrial ecosystems.

The goal of this paper is to compare the estimates of C stocks and flux in forest ecosystems of the St. Petersburg region (Russia) based on forest inventory summaries and Landsat-based models of forest attributes. We attempt to reconcile those estimates, identify sources of discrepancies, strengths and limitations of both methods, and propose an approach to integrating the two that would combine their strengths and compensate for limitations. To meet our goal, we combined some previously published results (Oetter et al., submitted, Treyfeld et al., 2001, submitted, Krankina et al., in press) with new data analysis and modeling.

2. Methods

2.1. GENERAL APPROACH

Total forest area and a set of forest cover attributes needed for modeling C stocks and flux were estimated by two independent methods: transformation of forest inventory data and modeling based on Landsat Thematic Mapper (TM) imagery. Because it is difficult to align the two data sources in space and time, we used three different spatial coverages (Fig. 1): (1) the entire St. Petersburg region, (2) individual Landsat scene, and (3) individual Forest Management Enterprise (Forest), which is the primary forest management unit in Russia (Kukuev et al., 1997). Methods for deriving a C stock estimate from forest inventory data (Treyfeld et al., 2001, submitted; Alexeyev and Birdsey, 1998) and for mapping vegetation cover types, forest biomass, and age (Oetter et al., submitted; Krankina et al., in press) were published in detail elsewhere and therefore are presented here in brief. We explain in detail the method for modeling C flux, that is based on the premise that C is a conserved quantity; thus, we may estimate net C flux (sink or source) as change in C stock over time. Estimates of C stock and flux are made for live biomass which includes above-and below-ground parts and for total ecosystem biomass which includes live biomass, litter, coarse woody debris, and soils.

2.2. STUDY REGION

The St. Petersburg region is located in the forest zone of NW Russia between 58° and 61°N and between 29° and 34°E. The region occupies 8.1 million ha of land surface and currently 53% of this area is covered with forests. The natural vegetation belongs to the southern taiga type; major conifer species include Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) both growing in pure and mixed stands. After disturbance, these species are often replaced by northern hardwoods including birch (*Betula pendula* Roth.) and aspen (*Populus tremula* L.). The climate is cool maritime with cool wet summers and long cold winters. The july mean temperature ranges from +16 to +17°C, and the January mean temperature is −7 to −11°C; mean monthly temperatures are below zero from November through March, and annual precipitation is 600–800 mm. The region is a part of the East-European Plain with elevations between 0 and 250 m a. s. l. The terrain is mostly flat and rests on ancient sea sediments covered by a layer of moraine deposits. The region was completely glaciated during the Ice Age, and contains numerous glacial features. Soils are mostly of the podzol type on deep loamy to sandy sediments. Numerous sites in the northwestern part of the region have very thin sandy soils and exposed granite bedrock, whereas the southern and eastern parts have deep silty soils and numerous expansive peat bogs. A large agricultural region stretches south and west from St. Petersburg, a city of over 5 million people. The St. Petersburg region has a long history of forest management dating from the 18th century. Most of the forests have been repeatedly harvested on 80–100 year rotation; fire control is very effective throughout the region.

2.3. FOREST INVENTORY DATA AND ESTIMATION METHODS

The estimates of forest area, calculations of C stocks in live forest biomass and their change over time were based on the recent forest inventory of 1993, and also on the data from the State Forest Accounts of 1988 (Drozhalov, 1990) and 1998 (Strakhov et al., 1999). These datasets report the area and wood volume (growing stock) for different categories of forest stands. The level of detail depends on the management status of forest lands with more detailed and up-to-date information available for lands under state forest management. These represent about 79% of all forest lands in the St. Petersburg region. Within these lands data to estimate biomass stores is available only for closed canopy forest, which is defined in Russian

TABLE I
Forest area, age, and carbon stores in the St. Petersburg region (Russia)

	Units	Forest inventory	Landsat analysis
Total forest area	10^6 ha	4.92[a]	5.48[b]
Forest area with data to estimate forest attributes	10^6 ha	3.39[a,c]	5.41[b]
Live forest biomass	TgC	269[a,d]	272[b,d]
	MgC ha^{-1}	54.7	49.6
Percent area dominated by hardwoods	%	33.7[a]	48.7[b]
Carbon sink in live forest biomass	MgC $\text{ha}^{-1}\text{yr}^{-1}$	0.36[a]	0.64[f]
Total forest area in Volkhov Forest[e]	10^3 ha	121.8	123.8
Live forest biomass in Volkhov Forest	TgC	7.5	8.1

Notes:

[a] *Source:* Treyfeld et al. submitted.

[b] *Source:* Oetter et al., submitted.

[c] Forests managed by the Federal Forest Service with relative stocking density >0.3 (corresponds to tree canopy closure >40%).

[d] Adjusted with area-based expansion factor.

[e] Excluding Porozhiskij Ranger district where forest inventory data was used as ground reference.

[f] For core Landsat scene (Figure 1).

forest inventory system as land with relative stocking density of trees >0.3 (corresponds to tree canopy closure >40%). Calculations of C stocks were limited to these forests, biomass on all other forest lands was not included in calculations. The regional totals of C stocks were estimated using area-based expansion factors (the ratio of the total forest area estimate to forest area under state management (Treyfeld et al., submitted)). Growing stock volume was converted into total live biomass (below- and above-ground) by adapting and modifying the system of conversion factors initially developed by Alexeyev and Birdsey for a country-wide assessment (Alexeyev and Birdsey, 1998). In addition to tree biomass, the stock of C in understory was calculated for the year 1998, this however proved to be a very small component (Treyfeld et al., submitted). The understory biomass was assumed to be constant and was not considered in calculations of changes in C stocks over time. In calculating C from biomass, a conversion factor of 0.5 was used. The forest inventory-based estimate of C sink in forest ecosystems is calculated as annualized change in live biomass C stocks between 1988 and 1998. Earlier inventories were not suitable for estimating C flux because inventory guidelines changed substantially several times prior to 1988 (Treyfeld et al., submitted). Estimates of forest area and C stock in live biomass based on the 1993 inventory data were compared with estimates based on Landsat imagery (Table I).

Because it is difficult to align the spatial coverage by forest inventory and remote sensing for the entire region, we also developed an estimate of C store for an

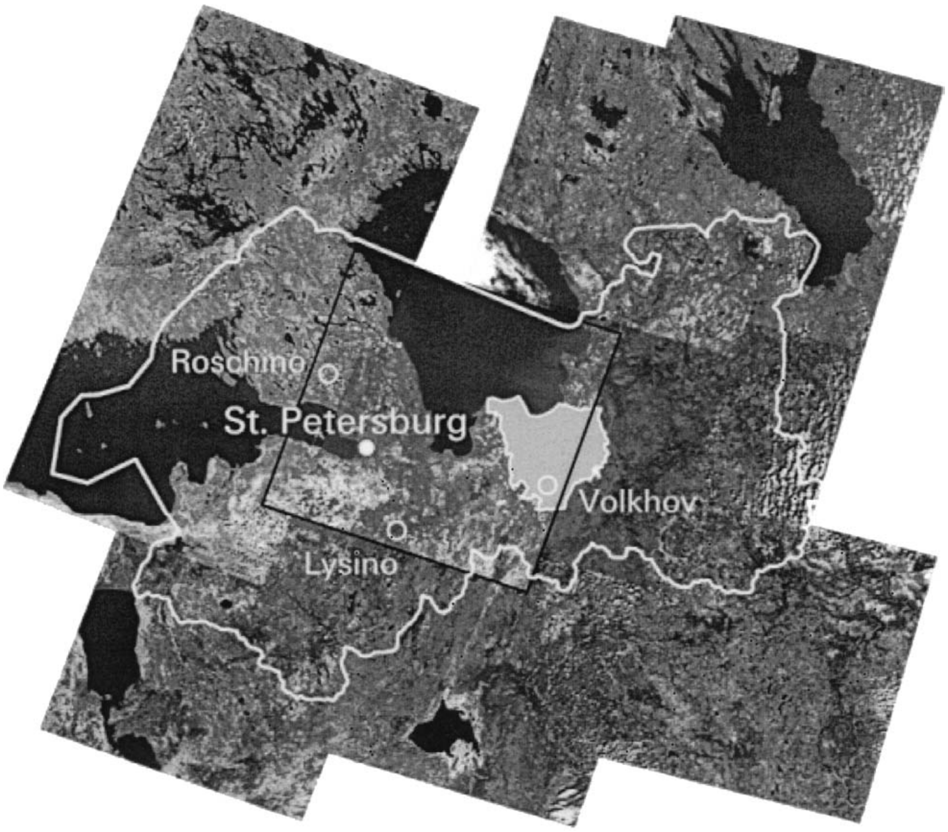

Figure 1. St. Petersburg region, locations of ground reference data, Landsat TM core scene, and Volkhov Forest.

individual forest within the region (Figure 1). The boundaries of the forest were digitized over Landsat core scene, total forest area, live forest biomass, and forest area distribution by age classes were calculated from stand-level database for the entire land area of Volkhov Leskhoz (Forest). One ranger district within the Forest was excluded because it was the source of training and test ground datasets for modeling forest cover attributes based on remotely sensed data.

2.4. REMOTELY SENSED DATA AND ESTIMATION METHODS

The method for mapping forest attributes using integration of ground reference datasets and Landsat satellite imagery was first developed for the Pacific Northwest (Cohen et al., 1995, 2001) and then was adapted for the conditions of the St. Petersburg region (Krankina et al., 1998, in press; Oetter et al., submitted). The selection of Landsat imagery was limited initially to the summer months (mid-May to mid- September) of 1992–1995 to match the time of the ground data collection. However, it proved impossible to find enough cloud-free imagery within that time frame to cover the entire region and scenes from 1986 and 1987 were added. Overall, 13 separate Landsat TM images and one Multispectral Scanner (MSS) image were acquired (Figure 1). Geometric rectification was performed using a map-registered base image (path 184, row 18 for 19 May 1992). Each of the 14 Landsat images was clipped to the St. Petersburg region boundary and subjected to multiple iterations of unsupervised classification, to construct a map with eight land cover classes (Agriculture, Bog, Built, Cloud, Forest, Shadow, Shrub/grass, and Water).

The spectral reflectance data for forest pixels were used for modeling of three continuous forest cover attributes—species composition, forest stand age (years), and live forest biomass (Mg ha^{-1}). Ground reference data for the model were derived from the database collected during the routine region-wide forest inventory of 1992–1993. We used one ranger district in each of three state forests (Roschino, Lysino, and Volkhov) that were selected to represent the variation in forest cover within the region (Figure 1). Forest inventory polygons (homogenous patches of vegetation delineated from aerial photographs) were referenced to Landsat imagery (Krankina et al., 1998). Field data for each polygon included tree species composition, age, wood volume, and characteristics of non-forest lands (bogs, clearcuts, and meadows). Biomass for each forest polygon was calculated from these data and available allometric equations (Alexeyev and Birdsey, 1998). From the total of 12 791 polygons in all three locations, non forest, small (<2 ha), and heterogeneous polygons were eliminated. This dataset included 1470 polygons and represented a very small fraction ($<0.2\%$) of the entire regional forest inventory database. Thus, the estimates by two methods were in essence independent, even though a subset of stand-level forest inventory data was used as ground reference data for modeling forest attributes with Landsat TM imagery.

The training and the test set each included 735 forest polygons separated into five forest cover types, depending on the relative dominance of forest tree species: (1) hardwood with hardwood cover $>70\%$, (2) pine with pine cover $>70\%$, (3) spruce with spruce cover $>70\%$, (4) mixed conifers with the sum of spruce and pine cover $>70\%$ but neither species alone $>70\%$, (5) mixed hardwood-conifer, which included all remaining polygons. The mean spectral signatures for polygons from these classes were extracted from 6-band TM layer, and a supervised classification was performed on radiometrically normalized TM mosaic of the entire region to separate the forested area into these five forest classes (Oetter et al., submitted, Krankina et al., in press). Within each forest cover type, predictive models relating spectral values to forest age and live biomass were generated using a 'reduced major axis' regression approach (Oetter et al., submitted). The correlation of multispectral indices with forest age and biomass was examined on the test set of polygons. It was statistically significant (at $\alpha = 0.05$) in all cases with higher correlation coefficients for biomass ($R = 0.53 \div 0.65$) than for age ($R = 0.19 \div 0.59$). RMSE for individual forest types ranged between 35 and 51 Mg ha^{-1} for biomass and between 15 and

30 years for age (Krankina et al., in press). Other studies of forest attribute prediction with Landsat TM data have found similar accuracy (Hyyppaa et al., 2000).

The greatest change in C stocks occurs in young forests: following timber removal slash, stumps, and roots decompose and release large quantities of C into the atmosphere, with time forest growth gradually offsets this release and forest stand begins to accumulate C (Cohen et al., 1995, Harmon and Marks, 2002). Although it is obviously important to map young forests accurately, this can be difficult because on satellite imagery young forests are easily confused with shrub lands, bogs and some types of agricultural lands (e.g. overgrown pastures, orchards). To improve the mapping of young forests (<4-years old) recovering after disturbance (mostly clearcut harvest) and their separation from shrub, agriculture, and bogs we overlaid these classes on our core scene with Landsat TM image path 184, row 18 for 27 June 1988. Clusters of pixels that appear as forest on 1988 image were confirmed or reclassified as young forest; all others (0.08^*10^6 ha) were presumed to be non-forest and excluded from the calculation of change in C stocks.

2.5. MODELING CHANGE IN C STOCKS

The change of C stocks in stand-level forest biomass was modeled with STANDCARB, which simulates the accumulation of C over forest succession (Harmon and Marks, 2002). Monthly climate-related variables control tree establishment, growth, and decomposition, whereas output is calculated on an annual time step and includes 10 state variables for live biomass components, nine state variables for detrital components, and three state variables related to wood harvest. Thus the model predicts net change in C stocks on site, but does not track the fate of C removed by timber harvest. The model was initially developed and parameterized for the Pacific Northwest (Harmon and Domingo, 2001; Harmon and Marks, 2002) and later was adapted and parameterized with local data for the conditions of the St. Petersburg region of Russia to simulate the growth of high productivity spruce (Griaznov et al., submitted). We calibrated the model to match changes in wood volume with stand age in local growth tables adjusted for average stand density (Moshkalev et al., 1984). Projections were made for forests up to age 150 years because of the lack of data for model calibration beyond that age and because very few stands in the region exceed the age of 150 years.

The average of 5 model runs was used to represents changes in C stocks per ha following clearcut harvest for five productivity classes and three major tree species in the region (pine, spruce, and birch) for which growth tables were available (Figure 2). We then simulated the growth of a mixed forest for five productivity classes as defined by forest inventory guidelines used in the forest inventory (Figure 3). The simulated species mix agreed with common species distribution across the productivity range: spruce dominated in high- and medium-productivity runs and pine was projected to dominate in medium-low and low-productivity

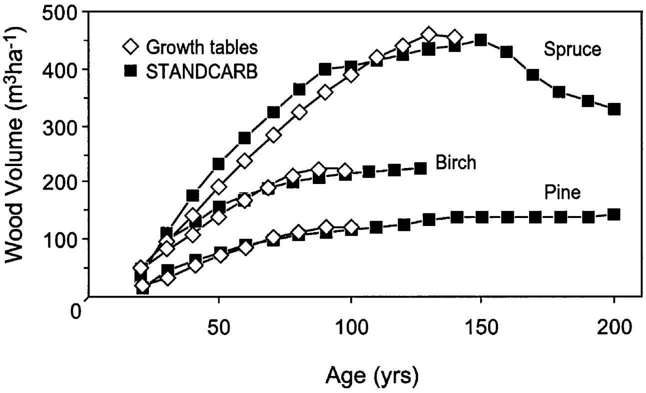

Figure 2. Comparison of calibrated STANDCARB model runs to local growth tables (Moshkalev et al., 1984) for the major tree species and different productivity classes (examples).

classes. Model outputs included C store in live forest biomass and the total ecosystem C store (including litter, coarse woody debris, and soil). These outputs were used to calculate the annual change of C store in live forest biomass and in toal ecosystem C stock (Figure 4).

To map the distribution of C sources and sinks we first combined the Landsat-derived maps of forest biomass and age within our core Landsat scene (Figure 1). Biomass and age values for each pixel were used to assign it to a productivity class with STANDCARB predictions for medium-high and medium-low classes serving as dividers (Figure 3). All pixels with ages 1–20 years were presumed to be in medium productivity class because biomass in young forests in highly variable and no growth tables were available to calibrate the model for young forests in different

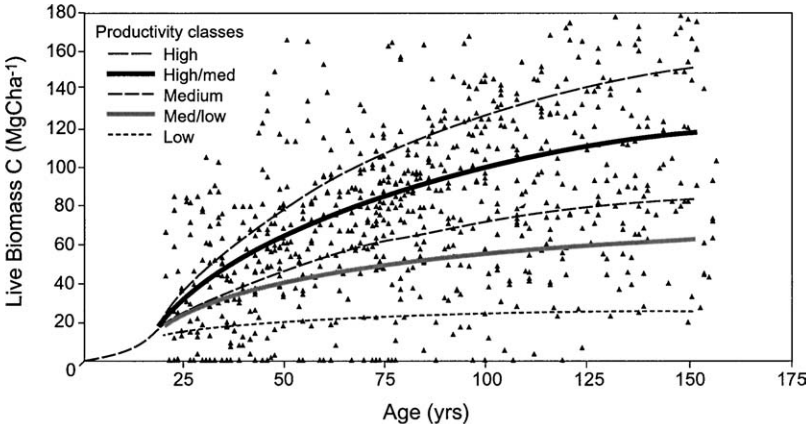

Figure 3. STANDCARB simulation of carbon stores in live forest biomass for mixed forest stands of five productivity classes and a scatter of random data points from Landsat-based regional maps of forest biomass and age.

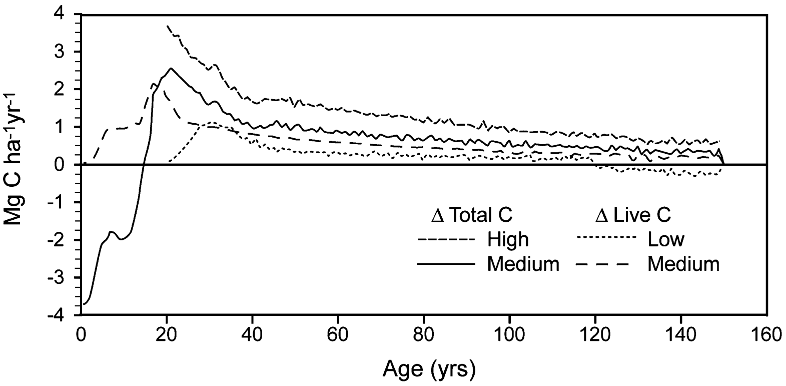

Figure 4. Annual change in total carbon store (Δ Total C) for high and medium forest productivity classes and in live biomass carbon (Δ Live C) for medium and low forest productivity classes.

productivity classes. The annual change in live biomass and total ecosystem C stock was assigned to each pixel based on age and productivity class. An increase in C stock was denoted with (+) and further referred to as sink, whereas a loss of C was denoted with (−) and referred to as source.

3. Results

The total forest area in the St. Petersburg region estimated by interpretation of Landsat imagery is significantly greater than the forest area reported by the regional forest inventory (Table I). Both methods provide extensive and consistent coverage of land surface, but exclude some portion of land from estimation of forest attributes needed to calculate C stocks and their change (species, growing stock or biomass, forest age). Landsat-based analysis excluded 1.3% of estimated total forest area due to scattered cloud cover, cloud shadows, and a small area mapped from older MSS imagery because no newer data were available. Forest inventory data did not provide estimates of forest attributes for 31% of the estimated total forest area; this includes lands that are not managed by the state and those that do not meet the definition of closed canopy forest. When adjusted with an area-based expansion factor, the regional estimate of total forest biomass based on forest inventory data agreed very well with the estimate derived from Landsat imagery (Table I). The forest inventory estimate of area dominated by hardwoods was smaller than the estimate based on remote sensing. A comparison targeting an individual forest within the region produced very close agreement in estimates of total forest area and adequate agreement in estimates of total C store in live biomass and forest area distribution by age classes (Table I; Figure 5).

STANDCARB projects the net C flux in forest ecosystems ranging between −5 and +4 MgC ha^{-1} yr^{-1}. C losses greater than 3 MgC ha^{-1} yr^{-1} are limited to 3–4 year period following timber harvest, 15 years after harvest C accumulation in live biomass offsets the emissions and the net flux is predicted to become positive

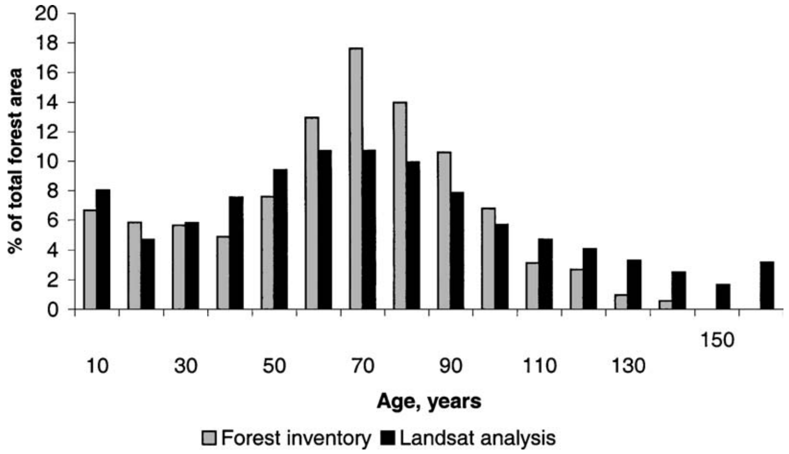

Figure 5. Distribution of forest area by 10-year age classes in Volkhov Forest of the St. Petersburg region.

(Figure 4). The highest rates C accumulation are predicted between ages 20 and 35 in forests of high productivity (2.4–3.6 MgC ha^{-1} yr^{-1}) and between ages 20 and 30 in forests of medium productivity (1.8–2.5 MgC ha^{-1} yr^{-1}. In low productivity forests the peak growth period is later and less prominent (0.7–1.1 MgC ha^{-1} yr^{-1} between ages 25 and 40). By the end of 150-year simulation the rate of C accumulation declines with forest age to 0.6 and 0.4 MgC ha^{-1} yr^{-1} in forests of high and medium productivity, respectively. Low productivity forests are projected to transition from a sink to a weak C source by age 120. The peak accumulation rate in live forest biomass occurs several years earlier than the peak of total C accumulation. The live biomass in forests of low productivity is projected to reach equilibrium by age 90 and the net change to fluctuate around 0 after that. High- and medium-productivity forests continue to accumulate C in live biomass at age 150 albeit at a very low rate (0.2–0.4 MgC ha^{-1} yr^{-1}) (Figure 5).

The flux of C was estimated for 1.07*10^{6} ha of forest land in the core Landsat scene (Figure 6) that covers about 20% of the total forest area in the region (Table I). The average age (68 years) and the average biomass store (57.5 MgC ha^{-1}) for the core scene were close to the averages reported by forest inventory for the region as a whole (62 years and 54.7 MgC ha^{-1}, Treyfeld et al., submitted). The greater part of the forest lands was actively accumulating C in live biomass: 52% of forest area was accumulating $\geq$0.5 MgC ha^{-1} yr^{-1}, and only a small proportion forest lands was losing live biomass (Figure 7). The total C sink in live forest biomass was 0.69 TgC yr^{-1} and the average rate of C accumulation in live biomass was 0.64 MgC ha^{-1} yr^{-1}, higher than the rate calculated from forest inventory data for the region (Table I). When total ecosystem biomass was considered, the forest area losing C to the atmosphere increased to 19% of the total. The spatial pattern of C sources and sinks was very intricate and the total of sinks (0.87 TgC yr^{-1}) exceeded total of sources (0.46 TgC yr^{-1}) for a net sink of 0.41 TgC yr^{-1} (or 0.38 MgC ha^{-1} yr^{-1}).

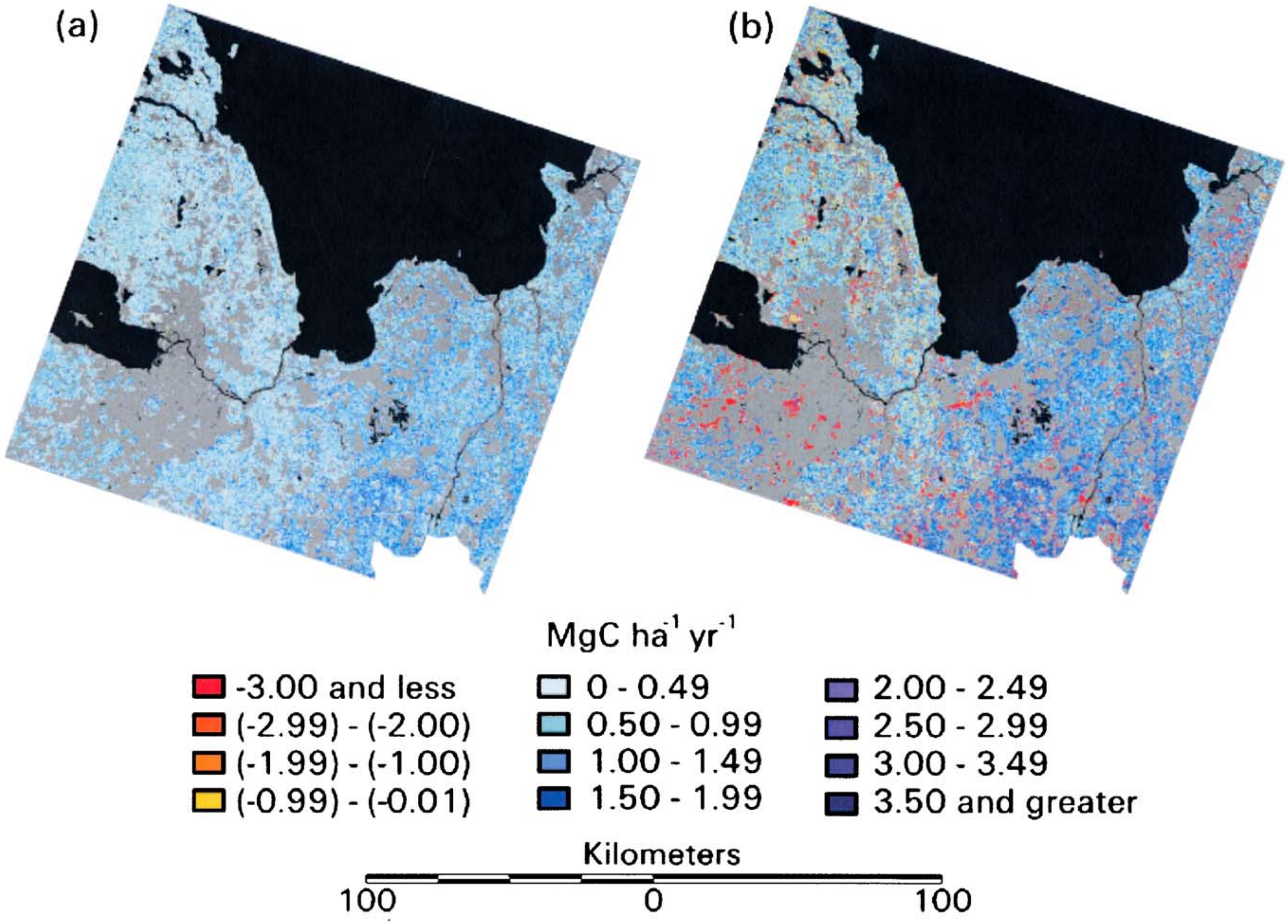

Figure 6. Carbon sources and sinks in forest ecosystems modeled on Landsat TM scene (path 182, row 18 for 19 May 1992): (a) live forest biomass, (b) total ecosystem biomass (color).

4. Discussion

The comparison of regional estimates of forest cover and its attributes based on forest inventory and remotely sensed data is ambiguous, even when the definition of forest is consistent between the two methods. Forest inventories focus on lands that are managed for timber production and tend to cover with lower frequency and accuracy forests that are managed for other primary goals. For estimating forest area with Landsat data, cloud cover is a major constraint. This tends to be especially significant in maritime regions and high latitudes where vegetation season is short and cloudy. However, when there are no stringent requirements to report data for a specific year and the best available data can be selected from the available archive of imagery, remote sensing can provide a virtually complete area coverage.

The estimates of live forest biomass in the St. Petersburg region agreed very well between the two data sources, but they apply to different forest areas (Table I). The difference in area estimates is attributable to exclusion of several types of tree-covered lands from forest inventory (e.g. parks, resorts, small woodlots around summer homes). In the estimate of the regional forest biomass store, the omission of some forest lands from forest inventory was probably offset by slightly exaggerated estimates for lands covered. The biomass estimate extrapolates the inventory data collected on forest lands managed by the Federal Forest Service to all lands designated as forest. The forests of the Federal Forest Service are better stocked than forests managed by other agencies: in 1988 the average growing

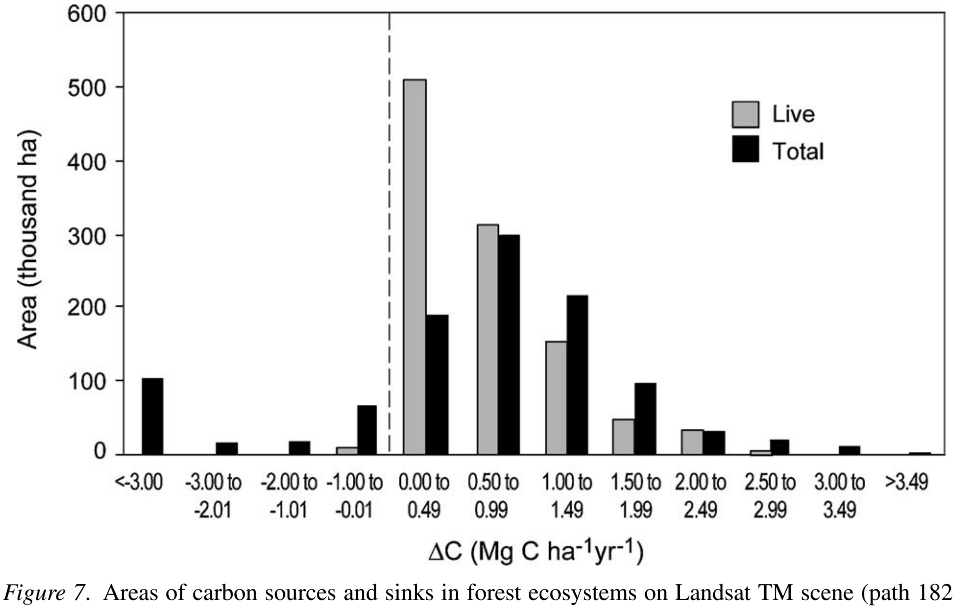

Figure 7. Areas of carbon sources and sinks in forest ecosystems on Landsat TM scene (path 182, row 18 for 19 May 1992).

stock volume on Federal lands was 169 m^3 ha^{-1} whereas other forest land had only 157 m^3 ha^{-1} (Drozhalov, 1990). In the St. Petersburg region forest inventories are repeated every 10 years on lands managed by the Federal Forest Service and the quality of data is among the best in Russia, yet even for this region the lack of adequate data for 'other' forests made it necessary to resort to extrapolation of data. In other regions of Russia in addition to incomplete area coverage, some of the data are over 40 years old (15% of forest lands, mostly in Eastern Russia; Kukuev et al., 1997). These limitations of inventory data are a mojor factor of uncertainty in estimates of current C stocks, sources, and sinks for Russia as a whole (e.g. Alexeyev and Birdsey, 1998; Goodale et al., 2002).

The Landsat-based estimate of biomass store for Volkhov forest exceeded the estimate based on forest inventory even though the forest area estimates agreed well (Table I). Landsat-based models were developed with ground data from different parts of the region to produce the robust estimates of mean and total values for the region as a whole. Different models would be needed for estimates on smaller areas with ground data focused on the area of interest. Fortunately, a large portion of forest land in the St. Petersburg region is covered with forest inventory data (Table I) and only a small fraction of it was used in this study. The fusion of the forest inventory databases with remotely sensed data offers opportunities for more precise mapping of C sources and sinks in the region.

There are significant differences between estimates of the regional C sink in live and in total ecosystem biomass (Figures 6, 7). C accumulation in live biomass averaged over the entire forest area (0.64 MgC ha^{-1} yr^{-1}) was significantly higher than accumulation rate in total ecosystem biomass (0.38 MgC ha^{-1}). Further, a significant portion of forest land was a net source of C to the atmosphere, whereas estimates for live biomass alone indicate C sink on virtually the entire forest area. This is because change in live biomass alone is only a partial estimate of C sink and if the goal is to provide an estimate of net exchange between forest land and the atmosphere, it is critical to include all biomass pools in calculation of C sinks.

The estimate of C sink in live biomass based on Landsat image interpretation and STANDCARB modeling does not include timber removals or any other forms of disturbance, whereas the estimate based on forest inventory-does. Timber harvest is the major disturbance factor which affects 35 000–40 000 ha annually whereas the area affected by fires averages <3000 ha annually. Virtually all timber from burned forests is salvaged and is therefore included in harvest statistics. The regional timber removal in 1993 was $4.64*10^6$ m^3, which is equivalent to $5.15*10^6$ m^3 wood volume on stump (Treyfeld et al., submitted). Converted to live biomass C with Alexeyev and Birdsey (1998) conversion factor for mature spruce (0.632*0.5) and averaged over the entire forest area in the region, the loss due to timber removal is estimated at 0.30 MgC ha^{-1} yr^{-1}. This brings the sink estimates by both methods (Table I) into good agreement.

The resulting estimates of net C sink in live biomass (0.34 and 0.36 MgC ha^{-1} yr^{-1}) are in line with 0.3 MgC ha^{-1} yr^{-1} projected for the western part of Russia in 1981–1991 by Myneni et al. (2001). UNECE (2000) reports similar values for the forests of Finland, Sweden, and the temperate estern U.S.A. However for Russia, their estimated sink of 0.48 MgC ha^{-1} yr^{-1} is substantially higher than our estimate. The UNECE (2000) study used current increment of wood as a basis for calculating the C sink and this parameter is readily available from forest inventories based on sample plots (U.S.A. and many West-European countries). However, current increment is not readily available from survey-based inventory systems such as those in Russia (Kukuev et al., 1997) and some other countries (Canada, China). The annual increment reported by these inventories is the average growth rate over the lifespan of forest (i.e. mean annual increment rather than current annual increment) and because old (mature and over-mature) forests dominate the Russian forest resource (Alexeyev and Birdsey, 1998), the use of mean annual increment as a substitute for current increment leads to an over-estimate of C sink by UNECE (2000).

The current net C sink in live forest biomass results from the history of forest use in the St. Petersburg region, in particular the low timber harvest in recent years. During this time the sustainable allowable cut for the region ranged between 7–8 million m^3, but the amount actually harvested was lower: 50–65% from 1960s to early 90s and only 43% in 1993 (Treyfeld et al., submitted). This led to accumulation of live biomass on forest lands, an increase in average age of forest stands, and corresponding changes in other forest attributes. The current C sink is probably smaller than 20–40 years ago when the largest cohort of forest stands (currently 50–80 years old, Figure 5) was at the peak of C accumulation (Figure 4). The current accumulation of C in live forest biomass will likely continue into the future unless there is an increase of timber harvest to twice 1993 level. This appears logistically and economically impossible in the near future. However, if the current sink estimate for the **total** ecosystem biomass is adjusted for biomass losses to timber harvest (0.38 minus 0.30 MgC ha^{-1} yr^{-1}) the net result suggests that the actual C sink on forest lands in the region is quite weak (0.08 MgC ha^{-1} yr^{-1}) and could be reversed by minor increases in harvest rates or a small decline in biomass growth rates.

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