# PROCEEDINGS

# The Role of Boreal Forests and Forestry in the Global Carbon Budget

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C.H. Shaw and M.J. Apps, Editors

Canadian Forest Service
Natural Resources Canada
Northern Forestry Centre
5320-122 Street
Edmonton, Alberta, Canada
T6H 3S5

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# RESERVES AND DENSITY OF ORGANIC CARBON IN FORESTS OF RUSSIA

**Anatoly I. Utkin, Dmitry G. Zamolodchikov, Georgy N. Korovin and Olga V. Chestnykh**
Centre for Problems of Ecology and Productivity of Forests (CEPL),
Russian Academy of Science,
117810 Russia, Moscow, Prosoyuznaya str., 84/32
e-mail:autkin@cepl.rssi.ru
e-mail:dzamolod@cepl.rssi.ru (corresponding author)
e-mail:korovin@cepl.rssi.ru
e-mail:olga@ochestnykh.home.bio.msu.ru

## ABSTRACT

Reserves of organic carbon (C) were estimated for phytomass ($C_{phytomass}$), soil without coarse woody debris ($C_{soil}$), and as totals ($C_{total}$). Preliminary estimates for C of coarse wood debris ($C_{CWD}$) were calculated based on simple assumptions. Estimates were done for three landscape subzones (the northern, middle, and southern) within each of four macro-regions (European-Ural, West Siberia, East Siberia, and Far East) using data from 59 ecoregions in the Asian part, and 56 federal districts in the European part, of Russia. These data include: (a) state forest inventory; (b) phytomass estimates for forest stands; (c) averaged phytomass estimations for meadows, peat bogs, and other non-forest areas, and (d) reserves of $C_{SOIL}$ for stands of the dominant tree species, both for non-forested areas and non-forest lands, according to data of the Russian Forest Fund (RFF).

The total land area in the RFF is $1110.5 \times 10^{6}$ ha. The total reserves of $C_{phytomass}$ and $C_{soil}$ were estimated at $34.35\times10^{9}$ t C and $172.43\times10^{9}$ t C, respectively. $C_{CWD}$ was estimated at $3.6\times10^{9}$ t C. $C_{TOTAL}$ in the RFF was estimated at $210 \times 10^{9}$ t C. If all types of forest land ownership are considered, the land area of Russian forests must be increased by 8%. Therefore, $C_{total}$ may be as high as $238.8\times10^{9}$ t C, including $C_{phytomass}$ ($36.92\times10^{9}$ t C), and $C_{soil}$ ($182.82\times10^{9}$ t C). The distribution of $C_{phytomass}$, $C_{soil}$, and $C_{total}$ is shown for four macroregions and three subzones within every macroregion. The density of $C_{total}$ ranges from 170-202 t C ha$^{-1}$ for macroregions and 179-202 t C ha$^{-1}$ for the three landscape subzones. $C_{phytomass}$ estimates range from 24-39 t C ha$^{-1}$ for macroregions and 18-48 t C ha$^{-1}$ for subzones. The ratio $C_{soil}/C_{phytomass}$ exhibits a similar distribution pattern and values ranged from 2.4 to 3.9 for the regions and from 2.6 to 5.5 for the subzones.

## INTRODUCTION

Nearly one-quarter of the globe's forest reserves can be found in the Russian Federation (RF). Forests cover 45.3% of the area which includes $774 \times 10^{6}$ ha of closed forests and a growing stock of $82 \times 10^{9}$ m$^{3}$ (Lesnoi Fond Rossii, 1999). The contribution of Russia to the world's standing stock is about 50% of coniferous forests and about 10% of deciduous forests.

The resource potential of Russian forests is well-known. Their ecological potential and contribution to processes in the biosphere functioning, including the carbon cycle, is less well understood. The absence of reliable estimates for net primary production (NPP), net ecosystem production (NEP) and, especially, net biome production (NBP) for Russian forests creates uncertainty about published patterns for the current carbon budget and forecasting it's response to global changes.

Understanding the carbon cycle in forests of Russian Eurasia is complex for many reasons, including an inventory of carbon and phytomass (plant biomass) in the territory of the Russian Forest Fund (RFF) is not a primary goal of the forest administration. Therefore, data acquired by soil scientists, geobotanists, and foresters over the course of the International Biological Program (IBP) and in the 1980-1990's, are hitherto basic to understanding the problem of carbon cycling in Russian forests.

Landscape maps, patterns of natural regions in the territory and other means were initially used for estimating pools and carbon fluxes in the former USSR and RF. The areas within different contours were scanned from maps using various techniques. Sometimes GIS-technologies were used. Area parameters were multiplied by averaged estimates of phytomass (carbon) for the same plant contours.

The method of integrating data from the RFF inventories and data on biological productivity for different types of forest ecosystems was later instrumental to estimating phytomass in Russian forests (Mackarevsky, 1991; Isaev et al., 1993, 1995a, 1995b; Alexeyev and Birdsey, 1994, 1998; Kolchugina and Vinson, 1995; Nilsson and Shvidenko, 1998; and others). Surveys for different regions of the RF were used in doing so. Estimations of soil carbon reserves were made using small scale soil survey maps (Orlov et al., 1996; Rozhkov et al., 1997). The same methods were used to estimate carbon pools in peat bogs and in soils of swampy forests (Vomperskij et al., 1996, 1999).

In this study estimates of phytomass carbon ($C_{phytomass}$), soil plus soil litter ($C_{soil}$) and total carbon ($C_{total}$) were mated with information from the RFF inventory. We think this approach is more reliable compared with scanning large-scaled maps for determination of land areas.

Data of the RFF inventory concerning areas and wood stocks distributed by age groups for stands of the main tree species or, more rarely, their combinations (coniferous, hardwood, and softwood) and for shrub species were used for estimating $C_{phytomass}$ in closed forests.

In this work carbon pools were estimated in the territory of the RFF divided into landscape subzones and macro-regions, although the former is emphasized in this paper. This method will increase the accuracy of calculations of $C_{phytomass}$ and $C_{soil}$ and therefore, must positively affect the estimation of carbon fluxes within the RFF.

## MATERIALS AND METHODS

### Data Sources

Our estimates used data from three different sources which include;

1. Inventory of the RFF;
2. Biological Productivity of Forest Ecosystems Database (Utkin et al., 1994) and,
3. Soil Carbon in Various Land Categories of RFF (Chestnykh et al., 1999).

The Inventory of the RFF has been conducted every five years since the latter part of the 1930's. The results are available in computerized form or as handbooks (Lesnoi Fond SSSR, 1990; Lesnoi Fond Rossii, 1995, 1999). The handbook includes various information used by forest managers and is differentiated at three territorial levels:

1. natural macroregions (the European-Ural part, West Siberia, East Siberia, the Far East);
2. natural-economic regions (13 regions) and,
3. federal districts of the RF.

The most abundant information is available for forests and forest lands of the Federal Forest Service of the Russia (FFS) which covers about 92% of the total forest territory.

The computer database "Biological Productivity of Forest Ecosystems" (Utkin et al., 1994) is the second principal source of information. It is a collection of data from the literature (about 750 references) which is continuously updated. It combines information on nearly 1500 forest ecosystems of the former USSR and other states in northern Eurasia with some data from North America. Comparison of phytomass data using allometric equations and regression analysis showed that genetically similar trees on both continents differ insignificantly (Hamburg et al., 1998; Utkin et al., 1998b).

The database provides information on;

1. location and environmental conditions;
2. stand structure and plant communities;
3. phytomass of the stand and the understory;
4. net primary production and,
5. forest litter and humus of the soil layer.

Data for tree age, density, stock, phytomass of stems, branches, foliage, and roots of the main forest-forming species were used to calculate phytomass/stock (Ph/S ratios). The latter were calculated using two approaches: (1) averaged statistical values (Isaev et al., 1993, 1995b) and, (2) values estimated as a function of stocking and age (Zamolodchikov et al., 1998). Furthermore, the possibility of estimating phytomass from the product of the sum of the basal areas and the mean stand height was checked (Utkin et al., 1998a).

Phytomass of the understory in plant communities is not directly dependant upon standing stocks. Therefore, it was estimated for stands as the mean of cuttings taken from sample plots. Age groups of stands were not considered. A similar method was used for non-forested lands (clearcut and burnt areas, and others) and for non-forest lands (meadows, bogs, and others).

The third source of data was the "Database on Soil Organic Carbon" which includes information on more than 1000 soil pits from 300 literature sources (Chestnykh et al., 1999). The database is continually updated and now includes data on forest soils, but information on "other lands" in the RFF is insufficient. Averaged estimates for soil organic matter per unit area were used to extrapolate to the regional scale.

**Structure of the RFF Inventory**

The inventory of RFF lands is conducted for three large land categories: (1) forested; (2) non-forested, and (3) non-forest lands. Each category is divided further into land types. Land types in the forested area are defined by the dominant species within the stand, non-forested areas by their origin (clearcuts, burns, and others), and in non-forest areas by type of land or landuse (hay-makings, pastures, roads, swamps, and so on). Forest-forming tree species are classified into three groups (1) coniferous, (2) hardwood deciduous (oak, beech, maple, ash, stone birch) or, (3) softwood deciduous (birch, aspen, alder, willows and others). Lands under shrub species are accounted for separately. These lands are often dominated by communities of dwarf Siberian pine (*Pinus pumila* (Pall.) Regel) and occupy an area of $38.3 \times 10^6$ ha (Utkin and Pryazhnikov, 1999). In addition, oak stands are differentiated into high-forest (seedling origin) and coppice stands.

Stands of the most abundant, or main forest-forming species are divided into six age groups:

1. young stands of the first age class;
2. young stands of the second age class;
3. middle-aged stands;
4. premature ;
5. mature and,
6. over-mature stands.

With the exception of young stands, the actual age of stands within any group may differ significantly depending on the age to stand maturity.

Ph/S ratios were estimated to calculate $C_{phytomass}$ for most of the main forest-forming species. Calculations for other tree species were done using mean Ph/S ratios for the three species groups previously described.

**Forest Zones of the RF**

The borders of the territories of many federal districts in the RF are meridionally defined and do not harmonize with existing natural forest regions. Therefore, we separated Russian forests into three landscape bands: (1) northern, (2) middle, and (3) southern, according to the landscape map of Isachenko et al. (1988). The boundary between the northern and middle subzones passes through somewhere around 63°- 64° north latitude in Europe and Siberia and 66° in Far East. The boundary between the middle and southern subzones passes through somewhere around 52°-60° north latitude with some shifting in a southward direction in the Far East. Vegetation of the mountains was defined by associated subzones at lower latitudes. Vertical zonality of landscapes was not considered.

**Calculations Methods**

***Correcting areas of RFF lands***

Since information on the forest fund of the RFF is basic, it can be applied to forest lands outside of the RFF. In the last two forest inventories correction factors were applied to different land categories to account for these additional forest lands.

The area of the additional forest lands is about 8% of the total area managed by the RFF. Distribution amongst the land categories in the additional forest lands is similar to the RFF, therefore estimates from RFF lands can be readily applied to the additional forest land in order to estimated totals for RF.

***Conversion of phytomass and soil organic matter mass to carbon***

Conversion coefficients per 1 kg of over-dried phytomass are 0.5 kg C for stems, branches and roots, and 0.45 kg C for needles, foliage, and understorey plants. The unified conversion coefficient equal to 0.57 kg C per 1 kg of soil organic matter was used for soil organic matter together with forest litter.

***Calculation of $C_{soil}$***

These values were estimated by analyzing data from corresponding databases and data from the forest inventory in 1993 (Lesnoi Fond Rossii, 1995). Using the database "Reserves of Soil Carbon in Lands of RFF" averaged reserves of organic matter were estimated for all land categories of the RFF including separate estimates for living forest-forming species on forested lands. Reserves of organic matter (t $ha^{-1}$) were converted to carbon (t C $ha^{-1}$). The latter values were taken as multipliers when calculating $C_{soil}$ reserves based on the areas of separate lands. Multipliers for $C_{soil}$ of different forest ecosystems were grouped by subzones and macroregions.

### *Calculation of $C_{phytomass}$*

Estimating $C_{phytomass}$ of stands from the database "Biological Productivity of Forest Ecosystems" (Utkin et al., 1994) was preceded by calculations of Ph/S ratios for all main forest-forming species within age groups of stands. First, individual relations for stems, branches, foliage or needles were determined. Their sum was taken as the coefficient for converting stand stocks to aboveground phytomass. Next, the share of stumps and roots within the total stand phytomass was estimated using the ratio of aboveground to belowground phytomass.

A corresponding parameter for estimating total phytomass was calculated after combining aboveground and belowground phytomass of stands and dividing this sum by volume reserves. Multiplying this parameter by 0.5 gave the ratio between carbon reserve and stem stock (C/S ratio) for stands of every forest-forming species within a defined age group. Analogous coefficients can be calculated through equations describing the dependence of C/S ratio upon the age of stands (Zamolodchikov et al., 1999).

$C_{phytomass}$ for non-forested and non-forest lands was estimated in the same manner as $C_{soil}$.

### *Calculations of total reserves of $C_{phytomass}$ and $C_{soil}$ for territorial contours at different levels*

Carbon reserves were converted from reserves of phytomass and soil organic matter determined separately for 59 ecoregions of Siberia and the Far East and for 56 federal districts in the European part of the RF. Reserves of $C_{phytomass}$ and $C_{soil}$ in macroregions and subzones were determined from total estimates for these 115 units.

Phytomass of all land categories in the RFF was estimated for each of the 115 units. A similar approach was used to calculate carbon reserves for soil organic carbon. Forest soil profiles were related to the forest-forming tree species, and stand age was ignored. Carbon reserves in peat were determined only to a depth of 100 cm instead of the whole peat layer. The integral parameters of $C_{phytomass}$, $C_{soil}$, and $C_{total}$ for an ecoregion or federal district were calculated by summing phytomass and soil carbon reserves for all types of land categories within a forest fund.

## RESULTS

### C/S ratios

Values of C/S ratios for stands of the main forest-forming species, with consideration for different age groups, revealed some general tendencies by subzones. The C/S ratio usually decreased in a southward direction and with increasing stand age. Relatively high values of C/S ratio are characteristic for younger stands. Values of C/S ratios for dwarf Siberian pine stands range from 0.8 to 1.2. Calculation of these coefficients took into consideration that long stem segments of *Pinus pumila* are buried under forest litter and in the upper soil layer, whereas estimating volume stock of the coppice was made by aerial photographs and concerned the visible parts of plants only (Utkin and Pryazhnikov, 1999).

### Reserves of $C_{phytomass}$ and $C_{soil}$ in the RFF

Data from forests and forest lands of the FFS were used as a basis to estimate $C_{phytomass}$ and $C_{soil}$ within four macroregions and three subzones (for 12 zonal-provincial regions). Although our results focus on the 12 regions, it is worthwhile to briefly consider pools of $C_{phytomass}$ and $C_{soil}$ of different forest land categories depending on age and species structure of the stands.

The total land area in the RFF is $1110.5\times10^6$ ha, consisting of 64% forests, 10% non-forested (burned areas, clearcuts, etc.), and 26% non-forest lands. The total reserve of $C_{phytomass}$ ($34.35\times10^9$ t C) is distributed between forests (98%), non-forested (1%), and non-forest areas (1%). The total reserve of $C_{soil}$ ($172.43\times10^9$ t C ) is distributed between forests (61%), non-forested (8%), and non-forest areas (31%). The $C_{total}$ ($206.78\times10^9$ t C) is distributed as follows: forests (66%), non-forested (8%), and non-forest areas (26%).

Within the forested area ($707\times10^6$ ha), 72% is coniferous, 2% is hardwood deciduous, 16%

is softwood deciduous, and 10% is other tree and shrub species. The distribution of $C_{phytomass}$ in the forested areas is 77% coniferous, 4% hardwood deciduous, 15% softwood deciduous, and 4% other. The distribution of $C_{soil}$ is 69% coniferous, 3% hardwood deciduous, 15% softwood deciduous, and 13% other.

The forested area is distributed by age of stands as follows:

1. young stands of two age groups (18%),
2. middle-aged stands (26%),
3. premature stands (10%),
4. mature and over-mature stands (46%).

$C_{phytomass}$ is distributed between these four groups as 6%, 25%, 12%, and 57%, respectively, and $C_{soil}$ as 16%, 27%, 10%, and 47%, respectively.

The part of the area occupied by older stands clearly increases in an eastward direction. In the European-Ural and West Siberia the percentage of mature and over-mature forests is only 7% and 6%, respectively, but in East Siberia and the Far East these values increase to 15 and 18%, respectively. The younger forests may play the most important role in $CO_2$ sequestration from the atmosphere in the two western macroregions. In contrast, forests of the two eastern macroregions mainly serve the purpose of carbon storage (Utkin, 1995).

The contribution of separate tree species to the carbon cycle is fully determined by the area they occupy. The most widespread forest-forming tree species in Russia are larch (37% of forested area), followed by pine (16%), birch (12%), spruce (11%), and Siberian pine (5%). Their individual contributions to $C_{phytomass}$ are 36%, 17%, 11%, 12%, and 9%, respectively, and to $C_{soil}$ 34%, 13%, 12%, 12%, and 8%, respectively. In total, the contribution of these five tree species is 81% of the forest area, 85% of $C_{phytomass}$ and 79% of $C_{soil}$.

Integral zone-macroregion estimates of $C_{phytomass}$ and $C_{soil}$ pools for forested areas of RFF are given in Table 1, and for non-forested together with non-forest lands in Table 2.

The total carbon reserve, without coarse woody debris, within RFF is estimated at nearly $207 \times 10^9$ t C, including forested (66%) and non-forested and non-forest lands (34%). The reserve of $C_{soil}$ is five times greater than $C_{phytomass}$ for Russia as a whole. The degree to which $C_{soil}$ exceeds $C_{phytomass}$ depends on the ecosystem or region under consideration. On average, forest $C_{soil}$ exceeds forest $C_{phytomass}$ by a factor of 3.3, (ranging from 3 to 6 in 15 regions) compared with an average value of 24.3 for non-forested lands (range of 21 - 37). $C_{soil}$:$C_{phytomass}$ ratios are quantitatively related to the area distribution of different land categories within the RFF. In forests of the northern subzone the ratio $C_{soil}$:$C_{phytomass}$ is, on average, 20-30% (rarely up to 50%) higher than ratios for the middle and southern subzones. Minimal values of ratios (around 2) are characteristic for the southern subzone of the European-Ural and East Siberia macroregions. These territories have been exposed to the significant impact of forest fires in the past, and in the forest-steppe zone of Siberia this impact is evident today.

The dissimilar structure of RFF lands in separate macroregions of Russia agree with differences in forest cover and bog cover percentages. The forest cover percent or the percentage of forests within the total area of forests, are as follows by macroregions: European-Ural (39%), West Siberia (37%), East Siberia (56%), and the Far East (46%) (Lesnoi Fond Rossii, 1999). The bog cover percent or the percentage of non-forest bogs within the RFF, for the same macroregions are 12%, [illegible], 7%, and 7%, respectively. The highest values for bog cover percent occur in the European North and lowlands of West Siberia which agrees with the distribution of forest and shrub ecosystems on wet lands. The ratio $C_{soil}$:$C_{phytomass}$ is highest due to the large C reserves in the bogs.

### Carbon Density in $C_{soil}$ and $C_{phytomass}$ Pools

Carbon densities in the phytomass and soil (t C $ha^{-1}$) were calculated using integral estimates of $C_{phytomass}$ and $C_{soil}$ pools on forested, non-forested and non-forest lands, divided by the area of each zonal-provincial regions. Carbon density of the phytomass varies from 25 to 60 t C $ha^{-1}$ on forest lands over all subzones, with values increasing in a southward direction. Values of phytomass carbon density generalized for non-forested and non-forest lands, have no significant geographical differences and range from 5.4 to 8.2 t C $ha^{-1}$ . Unlike forest ecosystems, carbon density of phytomass on non-forested lands decreases in a southward direction. Such a tendency is consistent with a change in the dominant species of the plant communities. Mainly evergreen species of the families *Vaccinaceae* and *Cyperaceae* are replaced by

Table 1. Carbon reserves and density pools $C_{phytomass}$, $C_{soil}$ and $C_{total}$ in forested lands of the RFF for separate macroregions and subzones (mean values ± SE).

| Macroregion | Subzones | Area ($10^6$ ha) | Carbon reserves ($10^6$ t C) | | | Carbon density (t C $ha^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|
| | | | $C_{phytomass}$ | $C_{soil}$ | $C_{total}$ | $C_{phytomass}$ | $C_{soil}$ | $C_{total}$ |
| 1 | Northern | 53.58 | 2 121±148 | 7 921±854 | 10 041±1 002 | 39.6±2.8 | 147.8±15.9 | 187.4±18.7 |
| | Middle | 24.82 | 1 103±71 | 2 295±602 | 3 398±673 | 44.4±2.8 | 92.5±24.3 | 136.9±27.1 |
| | Southern | 58.55 | 3 491±321 | 6 190±893 | 9 682±1 214 | 59.6±5.5 | 105.7±15.2 | 165.4±20.7 |
| | As totals | 136.95 | 6 715±540 | 16 406±2 349 | 23 121±2 889 | 49.0±3.9 | 119.8±17.2 | 168.8±21.1 |
| 2 | Northern | 17.04 | 570±46 | 3 046±668 | 3 616±714 | 33.4±2.7 | 178.7±39.2 | 212.1±41.9 |
| | Middle | 28.32 | 1 233±80 | 4 023±716 | 5 257±796 | 43.6±2.8 | 142.1±25.3 | 185.6±28.1 |
| | Southern | 33.40 | 1 797±142 | 5 187±703 | 6 984±845 | 53.8±4.3 | 155.3±21.0 | 209.1±25.3 |
| | As totals | 78.76 | 3 601±268 | 12 255±2 087 | 15 856±2 355 | 45.7±3.4 | 155.6±26.5 | 201.3±29.9 |
| 3 | Northern | 14.18 | 469±37 | 2 848±574 | 3 317±612 | 33.1±2.6 | 200.8±40.5 | 233.9±43.1 |
| | Middle | 103.83 | 4 419±343 | 17 055±3 102 | 21 474±3 446 | 42.6±3.3 | 164.3±29.9 | 206.8±33.2 |
| | Southern | 99.56 | 5 943±433 | 15 304±2 270 | 21 247±2 703 | 59.7±4.3 | 153.7±22.8 | 213.4±27.1 |
| | As totals | 217.57 | 10 831±814 | 35 207±5 946 | 46 038±6 760 | 49.8±3.7 | 161.8±27.3 | 211.6±31.1 |
| 4 | Northern | 104.43 | 2 559±341 | 16 520±2 407 | 19 079±2 748 | 24.5±3.3 | 158.2±23.0 | 182.7±26.3 |
| | Middle | 132.70 | 5 882±505 | 17 063±2 008 | 22 946±2 514 | 44.3±3.8 | 128.6±15.1 | 172.9±18.9 |
| | Southern | 36.60 | 1 837±163 | 7 084±944 | 8 920±1 106 | 50.2±4.4 | 193.6±25.8 | 243.8±30.2 |
| | As totals | 273.73 | 10 278±1 009 | 40 667±5 359 | 50 945±6 368 | 37.5±3.7 | 148.6±19.6 | 186.1±23.3 |
| 1-4 | Northern | 189.23 | 5 719±572 | 30 333±4 503 | 36 052±5 076 | 30.2±3.0 | 160.3±23.8 | 190.5±26.8 |
| | Middle | 289.67 | 12 637±999 | 40 437±6 429 | 53 074±7 428 | 43.6±3.5 | 139.6±22.2 | 183.2±25.6 |
| | Southern | 228.10 | 13 068±1 059 | 33 765±4 809 | 46 833±5 868 | 57.3±4.6 | 148.0±21.1 | 205.3±25.7 |
| | As totals | 707.00 | 31 424±2 631 | 104 535±15 741 | 135 959±18 372 | 44.4±3.7 | 147.9±22.3 | 192.3±26.0 |

Note: Separate estimates for 59 ecoregions in the Asian part of RF and 56 federal districts of RF in the European-Ural region were used in calculating integral characteristics.

Macroregions: 1- European-Ural, 2 - West Siberia, 3 - East Siberia, 4 - the Far East.

Table 2. Carbon reserves and density pools $C_{phytomass}$, $C_{soil}$ and $C_{total}$ in non-forested and non-forest lands of the RFF for separate macroregions and subzones (mean values ± SE).

| Macroregion | Subzones | Area ($10^6$ ha) | Carbon reserves ($10^6$ tC) | | | Carbon density (t C $ha^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|
| | | | $C_{phytomass}$ | $C_{soil}$ | $C_{total}$ | $C_{phytomass}$ | $C_{soil}$ | $C_{total}$ |
| 1 | Northern | 21.25 | 148±21 | 3 966±437 | 4 113±458 | 6.9±1.0 | 186.7±20.6 | 193.6±21.6 |
| | Middle | 8.54 | 46±5 | 1 322±160 | 1 368±166 | 5.4±0.6 | 154.8±18.8 | 160.1±19.4 |
| | Southern | 10.94 | 71±7 | 1 509±174 | 1 579±182 | 6.5±0.7 | 138.0±15.9 | 144.4±16.6 |
| | As totals | 40.73 | 264±34 | 6 797±772 | 7 061±805 | 6.5±0.8 | 166.9±18.9 | 173.4±19.8 |
| 2 | Northern | 16.07 | 123±17 | 2 940±343 | 3 063±359 | 7.7±1.0 | 183.0±21.3 | 190.6±22.4 |
| | Middle | 23.89 | 141±16 | 4 726±523 | 4 867±539 | 5.9±0.7 | 197.8±21.9 | 203.7±22.6 |
| | Southern | 18.33 | 102±10 | 3 741±428 | 3 842±438 | 5.5±0.5 | 204.0±23.4 | 209.6±23.9 |
| | As totals | 58.29 | 366±42 | 11 407±1 294 | 11 773±1 336 | 6.3±0.7 | 195.7±22.2 | 202.0±22.9 |
| 3 | Northern | 24.22 | 198±23 | 4 456±596 | 4 655±619 | 8.2±1.0 | 184.0±24.6 | 192.1±25.6 |
| | Middle | 36.38 | 280±32 | 6 428±886 | 6 708±918 | 7.7±0.9 | 176.7±24.4 | 184.4±25.2 |
| | Southern | 19.24 | 109±12 | 3 382±461 | 3 491±473 | 5.7±0.6 | 175.8±24.0 | 181.5±24.6 |
| | As totals | 79.85 | 588±67 | 14 266±1 943 | 14 854±2 010 | 7.4±0.8 | 178.7±24.3 | 186.0±25.2 |
| 4 | Northern | 168.96 | 1 293±148 | 26 241±3 212 | 27 535±3 361 | 7.7±0.9 | 155.3±19.0 | 163.0±19.9 |
| | Middle | 47.75 | 357±39 | 7 764±1 087 | 8 121±1 126 | 7.5±0.8 | 162.6±22.8 | 170.1±23.6 |
| | Southern | 7.90 | 54±5 | 1 422±181 | 1 477±186 | 6.9±0.6 | 179.9±22.9 | 186.8±23.5 |
| | As totals | 224.61 | 1 704±192 | 35 428±4 481 | 37 132±4 672 | 7.6±0.9 | 157.7±19.9 | 165.3±20.8 |
| 1-4 | Northern | 230.50 | 1 762±209 | 37 604±4 588 | 39 366±4 797 | 7.6±0.9 | 163.1±19.9 | 170.8±20.8 |
| | Middle | 116.57 | 825±92 | 20 240±2 656 | 21 065±2 748 | 7.1±0.8 | 173.6±22.8 | 180.7±23.6 |
| | Southern | 56.41 | 335±34 | 10 054±1 245 | 10 389±1 278 | 5.9±0.6 | 178.2±22.1 | 184.2±22.7 |
| | As totals | 403.48 | 2 922±335 | 67 898±8 489 | 70 820±8 824 | 7.2±0.8 | 168.3±21.0 | 175.5±21.9 |

Note: Separate estimates for 59 ecoregions in the Asian part of RF and 56 federal districts of RF in the European-Ural region were used in calculating integral characteristics.

Macroregions: 1- European-Ural, 2 - West Siberia, 3 - East Siberia, 4 - the Far East.

grasses and herbs.

Carbon density in soils of forest and other land categories of the RFF increases in eastward and northward directions. The tendency of meridional changing $C_{soil}$ is expressed less clearly. This is especially true for East Siberia, where middle and southern subzones constantly lose carbon owing to forest fires in Yakutia and the Far East. Non-forested lands of the RFF have insignificantly higher $C_{soil}$ density compared with forest ecosystems. However, these differences are compensated for by the density of $C_{phytomass}$. As a result, the total carbon density ($C_{total}$= $C_{phytomass}$+$C_{soil}$) is rather similar in all ecosystem types within subzones, through zones and through provincial profiles across the whole Russia. This result indicates that it is acceptable to estimate the parameter of carbon density for the $C_{phytomass}$ and $C_{soil}$ pools using the same approach for separate ecoregions and federal districts of the RF, even though they have a different structure.

Figures 1 and 2 show the spatial differentiation of carbon density in $C_{phytomass}$ and $C_{soil}$ respectively. The RFF, especially in the Asian part of Russia, is characterized by low values for the density of the $C_{phytomass}$ pool. Forests growing under the best climatic conditions of the European-Ural macroregion, in the south of Siberia and in Primorsky krai must be considered as exceptions (Figure 1). The spatial distribution of carbon density in the $C_{soil}$ pool is nearly the reverse of that observed for $C_{phytomass}$. The maximum values for carbon density of soils mostly occur throughout the European North, West Siberia, and the northern part of the Far East (Figure 2). The high carbon density of $C_{soil}$ in these regions is attributable to the large areas of excessively wet lands and attendant low rates for decomposition of plant residues. In southern Siberia and Primorsky krai significant reserves of soil humus, instead of detritus accumulation, account for the high carbon density of $C_{soil}$ in these regions. Abnormally low values of carbon density for $C_{soil}$ in the middle and southern subzones of Yakutia and Zabaikal'e are undoubtedly related to frequent forest fires. The same can be said about other inland regions of Siberia and the Far East.

### Annual Accumulation of Carbon

Information on the eco-physiology of forest ecosystems in Russia is very scarce and devoted to certain forest-forming tree species. Therefore, estimating NPP for all species within forests, with differentiation of stands by age groups and other dendrological divisions, is not yet possible. Calculations of annual carbon accumulation provides a notion of the dynamics of organic matter production in forest stands and other plant communities within the RFF. Methods for the calculations are given in detail by Isaev et al. (1995b). They are based on: (1) the analysis of successive changes in phytomass (carbon) reserves when stands move from a younger to older age group and, (2) the assumption that areas of stands are distributed more or less uniformly by their calendar age, within their age groups.

Young stands are characterized by more intensive increments compared with premature, mature, and especially over-mature stands in accordance with the regularity of forest growth. It is assumed that there is no accumulation of carbon in over-mature forests. In over-mature stands the current accumulation of phytomass compensates for the loss of carbon due to tree mortality (in part or in whole).

Estimates of carbon accumulation in stands of all forest-forming trees by age groups for the macroregions of Russia suggest that forests of the European-Ural and West Siberia macroregions are best suited to maximizing carbon sequestration. The dominance of old stands in the structure of the forest funds of the two other macroregions in eastern Russia allows forests to act only as storage in the form of $C_{soil}$, from previously accumulated carbon.
The spatial diversity of annual carbon accumulation by ecoregions and federal districts (Figure 3) suggests that forest ecosystems with low potential for sequestration of atmospheric $CO_2$ are distributed throughout nearly 80% of the territory in the RF. The average annual carbon accumulation is no more than 1 t C $ha^{-1}$ $year^{-1}$. Nearly the same quantity of carbon transfers annually into forest litter and detritus (i.e. into the ecosystem components with the shorter period of carbon containment). As our calculations show, total accumulation of carbon within all lands of the RFF is estimated at $261.64\times10^{6}$ t C $year^{-1}$, including forests ($243.16\times10^{6}$ t C $year^{-1}$).

Carbon accumulation in the RFF is possible, even on a large scale, by creating young stands on large areas in the European

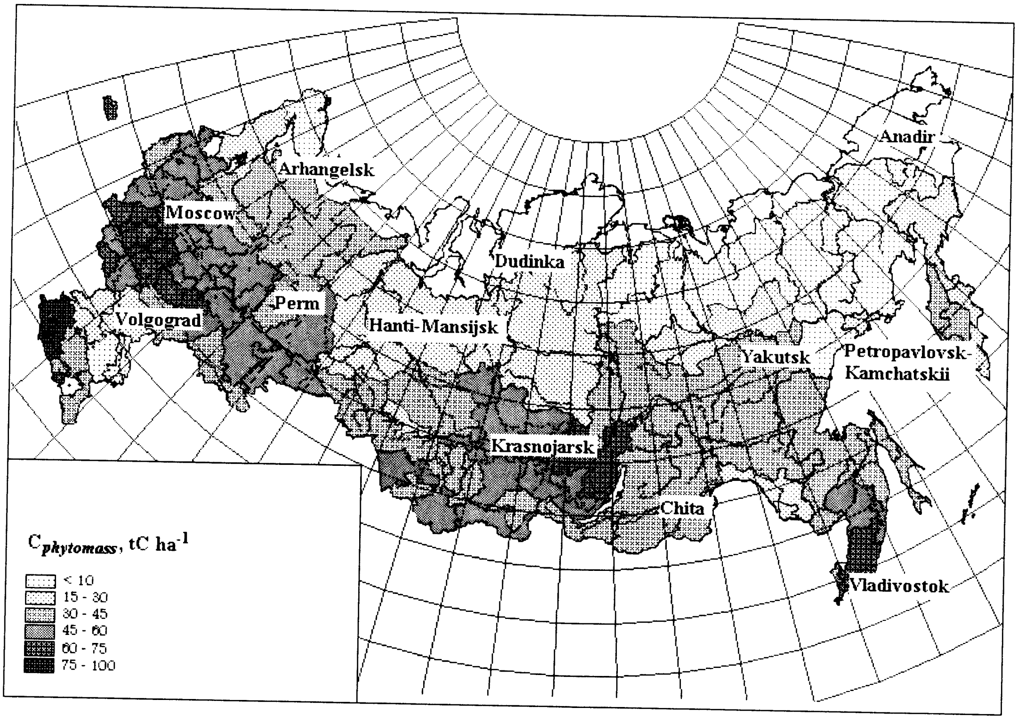


Figure 1. Geographic distribution of $C_{phytomass}$ density within the RFF of Russia.

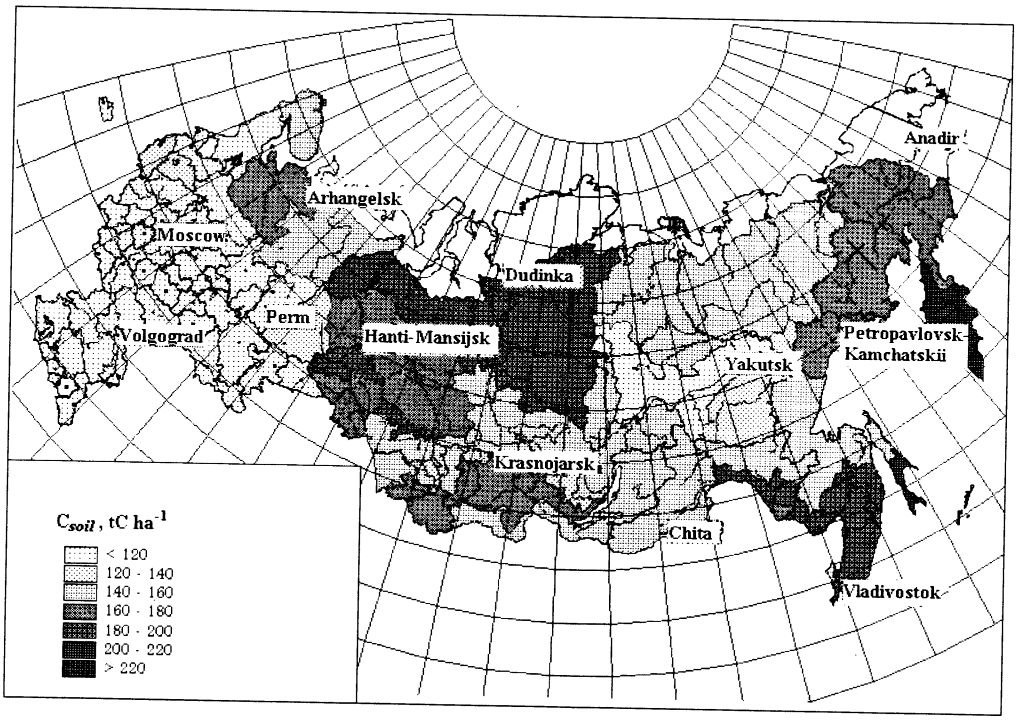


Figure 2. Geographic distribution of $C_{soil}$ density within the RFF of Russia.

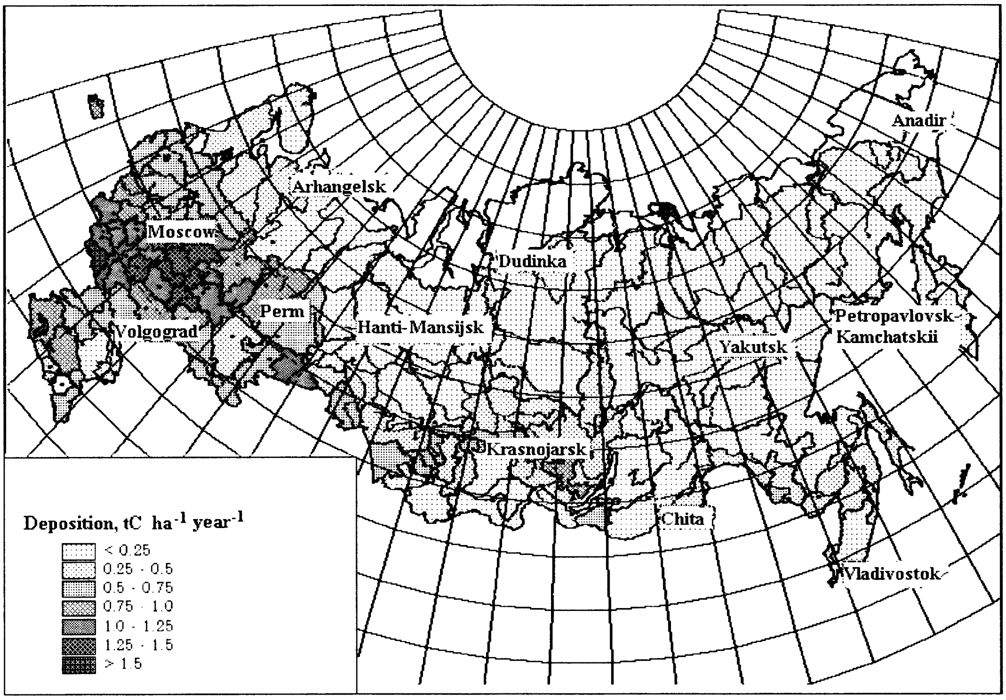


Figure 3. Geographic distribution of annual accumulation of $C_{phytomass}$ density within the RFF of Russia.

part of Russia and in the south of Siberia.

Rejuvenation of the forest fund in the northern and middle subzones of East Siberia and the Far East would be useful for the same purposes. However, large-scale reconstruction of the age structure of stands in these regions is not possible at present due to economic problems.

## DISCUSSION

The multistep procedure of calculating carbon reserves in forests managed by the RFF ($1110.5\times10^6$ ha) yielded estimates of $34.35\times10^9$ t C for $C_{phytomass}$, $172.43\times10^9$ t C for $C_{soil}$, and $206.78\times10^9$ t C for $C_{total}$.

The absence of data accounting for dead standing and windthrown trees prevents accurate estimation of the coarse woody debris carbon pool ($C_{CWD}$). A tentative calculation of $C_{CWD}$ was made to approximate actual conditions. The following assumptions were made in doing so:

1. reserves of CWD in forests and on previously forested areas (clearcuts, burns) are equal to 30% of available stand reserves;
2. one third of C reserves in CWD are accounted for by dead-standing trees having a wood density equal to 70% of the standard value for living tree species;
3. the wood density of windthrown trees (2/3 of the total CWD) is averaged at 50% of the standard one;
4. 90% of CWD occurs in forests, 10% occurs on clearcuts and burns.

According to our calculations, the pool of $C_{CWD}$ in the RFF is $3.6\times10^9$ t C; of which 90% or $3.15\times10^9$ t C is CWD in forests. Carbon of dead branches in living crowns also needs to be included. Their phytomass is assumed to equal about 10% of the total phytomass of branches and shoots of stands ($3.0\times10^9$ t C) which in turn corresponds to 15% of stem phytomass. Therefore the carbon reserve in dead branches of all stands in the RFF is equal to about $0.2\times10^9$ t C.

Once estimates for CWD are included, the total reserve of organic carbon in forests managed by the FFS of the RF is $209.95\times10^9$ tC, or approximately $210\times10^9$ t C. The estimate for the carbon reserve for all the forests in all of Russia is slightly higher. After applying the correction coefficients of 1.08 the estimate for the total carbon reserve ($C_{total}$) increases to $223.54 \times 10^9$ t C , which includes $36.92 \times 10^9$ t C for $C_{phytomass}$, $182.82 \times 10^9$ t C for $C_{soil}$, and $3.80 \times 10^9$ t C for $C_{CWD}$. $C_{total}$ is distributed between $150.15 \times 10^9$ t C in forests, $17.18 \times 10^9$ t C in non-forested lands, and $56.2 \times 10^9$ t C in non-forest lands.

The total estimate of $C_{phytomass}$ is slightly different from the ones we have published earlier (Isaev et al., 1993, 1995a, 1995b). This difference is due to the justification of the conversion coefficients C/S, more accurate evaluation of $C_{phytomass}$ in dwarf pine phytomass (Utkin and Pryaznikov, 1999), and RFF data extrapolation over the entire area of Russian forests. Comparison of our estimates for carbon pools on RFF lands with estimates of other researchers is difficult because of varying definitions for the carbon pools. For example, some authors combine $C_{CWD}$ and carbon into forest litter which is defined as "mortmass", others include forest litter in the $C_{soil}$ pool. Often calculations are made for forested land only, but not for all land categories of the RFF.

Data calculated by separate biomes are also of little use for comparison. Biome areas are defined by "recovered vegetation" and do not necessarily reflect the current regional structure of lands (Kolchugina and Vinson, 1993a, 1993b).

Alexeyev and Birdsey (1994, 1998) estimated $C_{phytomass}$ of Russia as a total land forest area and for forests in the RFF at only $29.53 \times 10^9$ and $27.98 \times 10^9$ t C, respectively. Nilsson and Shvidenko (1998) estimated $C_{phytomass}$ for the forested land area of RFF on the basis of state forest inventories in 1961-1993. They estimated the area of forested land in 1993 to be $763.5 \times 10^6$ ha (lower compared to statistical information, because of forest fires). Their estimates of $C_{phytomass}$ were $32.09 \times 10^9$ t C in 1993 and as $32.52 \times 10^9$ t C in 1988.

Some authors estimates of $C_{phytomass}$ for the forested land area of RFF are similar and range from $28.5 \times 10^9$ to $35 \times 10^9$ t C (Alexeyev and Birdsey, 1994, 1998; Nilsson and Shvidenko, 1998; the present work). However, our estimates of $C_{phytomass}$ reflect differences in areas and in values for C/S ratios.

Values for conversion coefficients C/S used in this study are higher than those used by Alexeyev and Birdsey (1994, 1998) and lower than those used by Nilsson and Shvidenko (1998). A very high coefficient of conversion for stand stock (0.53) is given by Kolchugina and Vinson (1993a) for all tree species. Also cited works did not apply a correction of the primary information on forests managed by FFS of RF to the total area of forests of Russia.

Published estimates of $C_{soil}$ are highly variable as well. Kolchugina and Vinson (1993a) estimated $C_{soil}$ of the former USSR at $320 \times 10^9$ t C, including forest litter at $338 \times 10^9$ t C, based on the areas of biomes. After converting for the RFF these estimates decreased to $314 \times 10^9$ t C and $321 \times 10^9$ t C, respectively. Alexeyev and Birdsey (1994, 1998), estimated $C_{soil}$, without forest litter, for the total forest land area at $140.3 \times 10^9$ t C (including $54 \times 10^9$ t C in peat on open bogs) and $74.16 \times 10^9$ t C for the forested land area. Others have estimated $C_{soil}$ at $129.6 \times 10^9$ t C to 1m depth of soil in the forested area of the RFF, and $8.72 \times 10^9$ t C in forest litter for a total of $138.32 \times 10^9$ t C (Nilsson and Shvidenko, 1998). Orlov et al. (1996) estimated $C_{soil}$ of forest soils in Russia, including areas partly utilized by agriculture, at $235.0 \times 10^9$ t C on an area of $1383.3 \times 10^6$ ha. Rozhkov et al. (1997) estimated the same parameters at $266.7 \times 10^9$ t C and $1316.5 \times 10^6$ ha, respectively.

Estimates of $C_{soil}$ are given in the present work at $172.44 \times 10^9$ t C for the total area of the RFF and at $67.2 \times 10^9$ t C for the forested area. These estimates are not consistent with estimates from other authors, with both overestimation and underestimation. The scatter of estimates for $C_{soil}$ is related both to variability of initial information on soil carbon density and to contradictory approaches to calculation of $C_{soil}$ in bogs. We think that uncertainty associated with estimates related to bogs is the most influential factor affecting variability in $C_{soil}$ estimates.

Bogs occupy an area of $125.2 \times 10^6$ ha within the RFF. They are present on other lands in forest zones (agricultural lands, nature reserves, etc.). If we use a value of 224 t C $ha^{-1}$ as a realistic estimate of carbon density for bogs, the capacity of carbon pool of peats is equal to $28.04 \times 10^9$ t C. Alexeyev and Birdsey (1994, 1998) estimated bog carbon at $54 \times 10^9$ t C which means, in this case, that the averaged carbon density of peat would be much higher at 431 t C $ha^{-1}$.

Vompersky et al. (1996) estimated the areas and carbon reserves of peats, using a soil map at a scale of 1:2 500 000. The area of peatlands, both forested and non-forest, in Russia is equal to $369.1\times10^6$ ha. The area of peatlands is $262.9\times10^6$ ha in taiga and other forest subzones (i.e. two times greater than in the RFF). Total carbon reserves in bogs with peat layers ≤ 30 cm and > 30 cm were estimated by Vompersky et al.(1996, 1999) at $12.6\times10^9$ and $100.93\times10^9$ t C, respectively, with average values of 55 and 726 t C $ha^{-1}$, respectively.

The range of averaged carbon reserves in peat bogs of the RF varies from 224 to 726 t C $ha^{-1}$ and is certain to influence the total estimate of $C_{soil}$ for the RFF since about 12% of lands within the forest fund are bogs. Obviously much effort is required to estimate $C_{soil}$, with some degree of confidence, for Russian forests as a whole and for their bogs in particular.

The information on $C_{phytomass}$ available for forests and lands within the RFF could be considered as sufficient and rather correct when combined with information from the state forest inventories. The same can not be said about data for $C_{soil}$. Therefore, calculating carbon macro-fluxes and forecasting changes in the carbon cycle should emphasize the dynamics of $C_{phytomass}$ until such time as $C_{soil}$ estimates can be improved. We recognize that sequestration of $CO_2$-C in $C_{soil}$ in Russian forests is as important as NPP and carbon accumulated in $C_{phytomass}$.

Data on carbon fluxes in forests of the RFF are scarce, presented by different characteristics, and fall in the category of expert estimates that often ignore carbon sequestration in $C_{soil}$.

Kudeyarov and Kurganova (1998) estimated the total annual emission of $CO_2$ for soils in Russia at $4.50\times10^9$ t C, and Bazilevich (1993) estimated NPP at $4.81\times10^9$ t C $year^{-1}$ suggesting a steady state between emission loses of $CO_2$ and carbon sink. Kolchugina and Vinson (1993b, 1993c) estimated NEP for forests of the USSR at $825\times10^6$ t C $year^{-1}$ and again at $662\times10^6$ t C $year^{-1}$ (Kolchugina and Vinson, 1995). Carbon sequestration in forests of the former USSR has been estimated at $416\times10^6$ t C $year^{-1}$ (Sedjo, 1992) and at $660\times10^9$ t C $year^{-1}$ (Kolchugina and Vinson, 1995).

In accordance with our data annual carbon accumulation is equal to $262\times10^6$ t C $year^{-1}$ including $243\times10^6$ t C $year^{-1}$ in forests (Isaev et al., 1995a, 1995b). It remains uncertain if carbon accumulation corresponds to NEP or NPP. Our observations on permanent plots in pine and birch stands over 30 years (from age 30 to 59 years) indicate that NPP is three times and NEP is two times, greater than accumulation. Using data from the "Bioproductivity of Forest Ecosystem: Computer Database" (Utkin et al., 1994) coefficients relating NPP to stand stock were calculated for the main forest-forming tree species (Zamolodchikov and Utkin, 2000). Combining these data with information from the state forest inventories, NPP of the main forest-forming tree species (without shrubs) was estimated at $1910.5\times10^6 \pm 386.5\times10^6$ t C $year^{-1}$ for aboveground phytomass and at $2267.6\times10^6 \pm 487.6\times10^6$ t C $year^{-1}$ for aboveground and belowground phytomass together.

Thus, we consider that the estimates for $C_{phytomass}$ in Russian forests are studied satisfactorily and in sufficient detail. But we cannot say the same about $C_{soil}$. Nevertheless, available results and patterns of estimating $C_{phytomass}$ with the use of information from state forest inventories is a useful approach to estimating carbon macro-fluxes including NPP, NEP, and NBP. Undoubtedly more reliable information on carbon cycling in boreal forests will become available in the immediate future. At that time, we will be better able to determine the magnitude of the importance of Russian forests in the C cycle of the biosphere. The strategy of forest management in Russia must be determined in light of these studies and their results.

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