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Carbon stock in living biomass of Russian forests: new quantification based on data from the first cycle of the State Forest Inventory

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Abstract

The carbon stock in living forest biomass was quantified based on first-cycle State Forest Inventory (SFI) measurements in permanent sample plots. The total carbon stock in above- and below-ground living biomass was assessed to be 46.9 ±0.4 × 10^9 tons C and average carbon stock at 52.1 ±0.5 t C ha^{-1} as of 2020. The State Forest Register (SFR), the primary source of consolidated information on Russia's forests, estimates the forest growing stock to be 83.1 × 10^9 m^3. The total growing stock volume in the forests, according to the SFI amounted to 113.1 × 10^9 m^3. Owing to the updated and significantly higher growing stock volume, the estimate of carbon stock in living biomass is approximately 35% higher than previously reported. The uncertainty of the total and average carbon stocks based on SFI data was substantially lower (approximately ±1%) than that reported in previous studies (±15–30%). Methods of accounting for the carbon stock in living biomass, the results of calculations for forest lands throughout the country, units of the administrative division, and forest zoning were considered. Assessment of living biomass based on representative sampling can substantially improve the relevance and reliability of national forest reporting.

Key words: Russian forests; living biomass; carbon stock; forest inventory; permanent sample plots

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1. Introduction

The conservation of forests and other terrestrial ecosystems as major carbon reservoirs and cycle regulators is recognized as a priority in global climate policy. This is evidenced by the Declaration on Forests and Land Use, signed by the leaders of 141 countries at the UN Climate Change Conference in Glasgow on November 12, 2021 (UNFCCC COP26 2021).

Assessing the mitigation potential of forests in the context of climate change and ecosystem forest services is a popular area of research (Kindermann et al. 2008; Grassi et al. 2018; Friedlingstein et al. 2022; Girona et al. 2023). Quantitative evaluation of the biomass of forest ecosystems, as well as the accumulated carbon stocks, is the subject of research by numerous scientific teams worldwide. Large-scale global and regional studies have been conducted using remote-sensing data (ESA DUE GlobBiomass 2010; ORNL DAAC 2010; Margolis et al. 2015; Pechanec et al. 2017; Santoro & Cartus 2019; Global Carbon Atlas 2021; Santoro et al. 2021; Spawn et al. 2021; Bastos et al. 2022;). Nevertheless, remote sensing data alone are insufficient to determine the amount of forest biomass, its distribution, and the reliability of estimates without ground-based surveys. Spatial data on forest biomass distribution obtained by combining multiple satellite observations requires validation against forest inventory data to assess uncertainty (Santoro 2018; Santoro et al. 2021). In Russia, multi-year and successful studies estimating the biomass and carbon stocks in forest biomass have been conducted by scientists of the VN Sukachev Forest Institute of the Russian Academy of Sciences (Alexeyev & Birdsey 1998), Ural State Forest Engineering University in cooperation with the Ural Branch of the Russian Academy of Sciences (Usoltsev 2002; Usoltsev et al. 2016), and the International Institute for Applied Systems Analysis (IIASA) (Shvidenko et al. 2009; Shvidenko & Schepaschenko 2014), and the Center for Forest Ecology and Productivity of the Russian Academy of Sciences (Zamolodchikov et al. 2018).

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The quantification of forest biomass and biomass carbon stocks is necessary for national reporting under international processes on forests in which the Russian Federation is involved, namely, the FAO Global Forest Resources Assessment, the UN Framework Convention on Climate Change, the UN Strategic Plan for Forests 2017–2030, and the UN Convention on Biological Diversity. National inventory reports on the Land Use, Land Use Change and Forestry (LULUCF) sector, as part of the implementation of obligations under the UNFCCC, provide information on annual removals/emissions of carbon that describes forest ecosystems as a sink or source of carbon. In this case, the carbon stock in living biomass served as the starting point for subsequent estimates. The Russian Federation's reports on the LULUCF sector were derived from the State Account of the Forest Fund (SAFF) until 2007, and the State Forest Register (SFR) after 2007. Similar to its predecessor (SAFF), the SFR provides consolidated statistical information on Russia's forests collected initially in the field at the forest stand level. International experience shows that the most accurate national estimates are derived from ground-based measurements of trees and other forest ecosystem components in sample plots. Such measurements are an integral part of the National Forest Inventory (NFI). A number of countries around the world with boreal and temperate forests have already completed several NFI cycles. For example, 12 cycles have been completed in Finland (Tomppo et al. 2011; Korhonen 2016; Korhonen et al. 2021), 10 in Norway (Breidenbach et al. 2021), 19 in Sweden (Fridman et al. 2014), and three each in the Czech Republic (Adolt & Kučera 2021) and Germany (Wellbrock et al. 2017).

In Russia, the SFI is a fundamentally new forest-counting system, the first cycle of which was completed in 2020. The results of SFI measurements have been published only in a fragmented manner, and the aggregate qualitative and quantitative characteristics of the country's forests and their regional distribution have still not been fully presented to the expert scientific community. According to the first publication of the SFI results, the total growing stock in the Russian Federation's forests was 113.1×10^9 m^3. The actual error in estimating the total growing stock was ±0.35% at the 95% confidence level, which was significantly lower than the planned error of ±1% (Analytical Review 2023). The average total volume of growing stock was 126 m^3 ha^{-1}. According to SFI data, the total forestland area in the Russian Federation amounted to 899.9 million ha. For comparison, the total growing stock volume in the national report of the Russian Federation for the recent FAO Forest Resources Assessment, based on statistical information from the SFR, was 83.1×10^9 m^3 over a similar area, with an average total of 104 m^3 ha^{-1} (FRA FAO 2020f). As can be seen from the above, the total growing stock volume in Russian forests, based on SFI data, exceeded that calculated using SRF data by more than 35%. This significant difference in growing stock can be attributed to differences in the accuracy of the inventory methods used. Input data for the SFR were derived from the forest inventory and planning operations at the forest stand level. The growing stock volume was determined with acceptable standard deviations from ±15 to ±30%, whereas systematic errors did not exceed 10% (Filipchuk et al. 2020). Instrumental tree measurements at the SFI sample plots, compared to eye-measured forest stand parameters during forest inventory and planning operations, provided a more objective assessment of the growing stock with greater accuracy. A similar effect was observed in the transition from a stand-level forest inventory and planning operations to tree measurements at sample plots in the first-cycle NFI in the Czech Republic. The difference in total growing stocks obtained after the transition to the sampling-statistical inventory was +38.5 %, with an error of ±1 % (Národní inventarizace lesů 2007).

The first-cycle SFI results are yet to be analytically understood. One practical application of this large dataset is to use the SFI to estimate the biomass and carbon accumulated by forest biomass to improve national reporting on climate and other international agreements. The transition from SFR data to SFI data implies a transition from the estimation of forests at the stand level to the assessment of statistically reliable forest characteristics based on the results of measurements of every tree at the permanent sample plot level. This is a qualitatively new approach to forest accounting in Russia, which entails updating sources of information and improving methods of processing this information, including national reporting.

This article focuses on the estimation of carbon stocks in the living biomass of Russian forests as of 2020, in accordance with the Intergovernmental Panel on Climate Change (IPCC) guidelines, and how SFI data can be used to improve national reporting. Previously, using two test objects as examples, namely, the region of coniferous and broadleaved forests of the European-Ural part of Russia and the Republic of Karelia, the possibility of applying SFI data to improve the estimates of forest carbon stocks for national reporting has been revealed (Filipchuk et al. 2021). This study presents the results of a new assessment of the carbon stock in the living biomass of Russia's forest lands as a whole as well as by units of administrative division and forest zoning as of 2020.

2. Materials and methods

Recognizing that the assessments of forest carbon parameters at the regional and national levels are still performed with considerable uncertainty, the IPCC welcomes improvements in methods and parameter recalculations as new data sources and assessment methods become available (IPCC 2006a). The input parameters

for the assessment of forest living biomass and carbon stock in living biomass were the areas of forest land by tree species, growing stock volumes, and the age structure of tree species.

2.1. Baseline data

The study area includes forestlands of the entire country and is subdivided by administrative units and units of forest zoning. As for the SFI data, the total forestland area in the Russian Federation amounted to 899.9 million ha, and approximately 90% of the area refers to boreal forests. Note that the forest land area was calculated using vector maps of the forest management inventory updated with orthorectified remotely sensed data. The major forest-forming species in Russian forests are larch (*Larix*), pine (*Pinus*), spruce (*Picea*), fir (*Abies*), Siberian pine (*Pinus sibirica* Du Tour), birch (*Betula*), aspen (*Populus tremula*), oak (*Quercus*), and others. Among the forest-forming species, larch ranks first by area, birch ranks second, and pine ranks third (Analytical Review 2023).

In this study, baseline data were derived by processing the measurements of individual trees in permanent sample plots (PSP). Over the 14-year period between 2007 and 2020, 69,100 PSPs with specific geographical locations were established across the country. The number of PSPs surveyed annually ranges from 4,000 to 5,000 and more. The SFI sample plots were located in all categories of forestland covered by land legislation, including the lands of the Forest Fund under the jurisdiction of the Federal Forestry Agency; forests on lands used for industry, transport, defense, security, and other special purposes; national reserves and national parks; and forest lands within human settlements (city forests). Inventory sample plots for non-forested land were not designed. Statistical and stand-level forest inventory data updated by remote sensing provide information about the characteristics of non-forested lands and their spatial distribution.

Sampling plots designed for the first-cycle SFI were stratified using a two-level approach (Alekseev et al. 2019). The first level of stratification was based on the division of the country into forest vegetation zones and forest regions within these zones with specific site growth conditions and forest productivity. The forest zoning units correspond to the forestry regulatory documents. Regulatory documents include eight forest vegetation zones and 42 forest regions within their boundaries. The required precision of the growing stock volume ranged from one to 10% depending on the forest region. The second-level strata within the boundaries of the forest regions were essentially subsamples of relatively homogeneous areas with similar forest development types. In practice, strata were formed from a set of forest patches with similar forest characteristics, such as a group of dominant tree species, age group, and yield class. Aggregation of forest patches was performed based on a stand-level forest inventory updated using remote sensing. Orthorectified remote sensing data were used to refine forest land boundaries, update the boundaries of land that had temporarily lost forest cover, and identify areas occupied by groups of tree species. In total, 49 strata were formed, including a separate stratum with temporarily deforested forest lands, namely, unclosed forest cultures, regenerated clear cuttings, burned and fire-damaged areas, dead tree stands, and natural sparse forests. Forestland areas were estimated based on vector maps of forest management inventory updated with remotely sensed data, controlling for the consistency of the sum of the areas by strata. The calculation of the number of PSPs in the stratum was carried out using a mathematical function including the mean growing stock volume per stratum, variance of stock volume per stratum, and the required precision of estimates of the growing stock volume.

The total size of the general population was calculated so that the required accuracy for determining the growing stock volume across the country was ±1% at the 95% confidence level. The actual accuracy of determining the growing stock volume was estimated at ±0.35% at the 95% confidence level, that is, it was higher than planned. The first cycle of the SFI used simple random sampling to design the PSPs in specific strata within boundaries of forest region. For practical reasons, the sample plots were organized into clusters in remote and hard-to-reach regions. Each cluster included 5–8 PSPs. The sampling intensity of the forest region in the first-cycle SFI is shown in Fig. 1.

All the established inventory plots of the SFI were permanent. The sample plot (0.05 ha) consisted of three concentric circles with fixed radii. All trees with diameter at breast height (dbh) ≥ 20 cm were measured within a circle with a radius of 12.62 m (area of 0.05 ha). Trees with dbh above 12 cm were measured within a circle with a radius of 5.64 m (area of 0.01 ha), and trees with dbh greater than or equal to 6 cm were measured in a circle with a radius of 2.82 m (area of 0.0025 ha). Two additional circular plots with 1.78 m radius located 5.64 m from the north-south PSP center, were used to describe the understory and undergrowth. The ground cover vegetation was examined in a strip 10 m long and 1 m wide, passing through the plot center from west to east. Deadwood was recorded over the entire sample plot. The configurations of the sample plots were similar in many temperate and boreal forest inventories, with different diameter thresholds at the breast height of the trees considered (Merganič et al. 2017; Šebeň et al. 2018; Alekseev et al. 2019). The similarities between the SFI and the NFI of the Czech Republic and Slovakia are because Czech specialists were actively involved in the development of the SFI methodology during the initial phase. Furthermore, the comprehensive Field-Map software

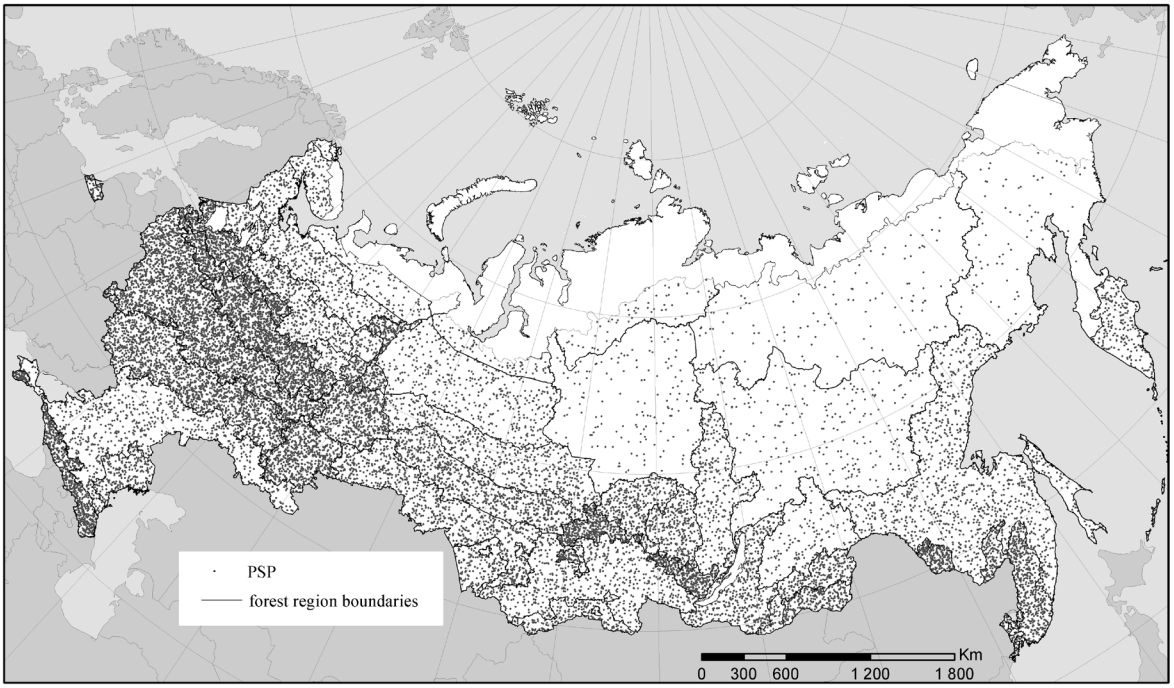


Fig. 1. Spatial distribution of first-cycle SFI plots within the boundaries of the forest regions. The administrative unit boundaries are shown in accordance with Russian legislation for the year of completion of the SFI first cycle, 2020.

and hardware technology from IFER Ltd. of the Czech Republic (Cerný et al. 2010) for collecting data in the field and subsequent data processing were used during the first cycle of SFI. The modified Russian version was called the Software and Information Complex of the SFI. In total, 117 indicators were measured and assessed for each PSP (Solontsov et al. 2016). For this study, we used the data of standing trees and shrubs measured within the PSP, excluding understory, deadwood, and ground cover vegetation.

2.2 Methodology

The living biomass was not measured directly in the field, but could be obtained indirectly based on stem volume. When indirectly estimating the living biomass and carbon stocks in living biomass, the most significant indicators obtained from processing the field measurements were the growing stock volume by tree species and age. The growing stock volume was calculated in the field based on the volumes of standing tree stems and tables of volumes specific to the Russian regions. Predictors for calculating the stem volume of a single tree on the sample plot were tree species, dbh, height, and tree crown height or diameter at one-third of the tree height. Generally, the carbon storage in living biomass increases with the age of forest stands (Wei et al. 2013). In the methodology used, the growing stock volume of tree species was divided into four age groups: 1) young, 2) middle-aged, 3) near-mature and 4) mature and over-mature. Notably, 31% of the total growing stock volume is formed by forests older than 120 years (mature and over-mature forest stands), according to the SFI (Analytical Review 2023). The age-specific allocation of growing stock volume by tree species to age groups is not straightforward. Regulatory documents governing the management of forests in Russia provide for categorizing the age of tree species into specific age groups depending on the age of maturity. In general, the maturity age of tree species varies according to site quality conditions, which are determined by forest zoning (forest vegetation zones). In practice, forestry regulatory documents set the tree species age of maturity by region depending not only on the forest site quality conditions, but also on the forest management designation, namely for environmental protection, exploitation (commercial harvesting), and reservation. The last category included forest lands that were not planned for merchantable wood harvesting in the next 20 years. To reclassify the volume of tree species of a certain age into age groups, a special recording table was compiled to reference tree species volumes of a certain age into age groups depending on the intended use of forests and forest site zoning. Measurements on the SFI sample plots were carried out in different years from 2007 to 2020 over a period of 14 years. Growth tables and models were used to adjust the merchantable growing stock volumes by forest species and age groups obtained from different years to 2020. Shvidenko et al. (2008) developed tables and models of

growth and productivity of major forest forming species recommended for use in forestry and forest management of Russia. The estimation of annual losses in merchantable volumes because of harvesting was based on annual forestry statistics. The original SFI data were processed to account for merchantable growing stock as of 2020.

In this study, the carbon stock in the living biomass was quantified by modifying the IPCC basic equation 2.8b (IPCC 2006b) as follows:

$$C = \Sigma_k \Sigma_{ij} \{A_{ij} \cdot V_{ij} \cdot BCEF_{sij} \cdot (1 + R_{ij}) \cdot CF\} \qquad [1]$$

where:
C – total carbon in above- and below-ground living biomass by units of administrative division, tons,
k – forest region (domain, k = 1 to 42),
i – tree species (i = 1 to n),
j – age group (j = 1 to 4),
A_{ij} – area of forest lands by tree species and age groups, ha,
V_{ij} – average merchantable growing stock volume by tree species and age groups, m^3 ha^{-1},
$BCEF_{sij}$ – biomass conversion and expansion factor applicable to growing stock that transforms merchantable volume of growing stock into aboveground tree biomass by tree species and age groups, tons d. m. m^{-3},
R_{ij} – root-to-shoot ratio (ratio of below-ground biomass to above-ground biomass) by tree species and age groups, dimensionless,
CF – carbon fraction of dry matter (for coniferous tree species = 0.5, for deciduous tree species = 0.47), tons C (ton d. m.)$^{-1}$.

According to the IPCC guidelines (IPCC 2003; IPCC 2006a; IPCC 2006b), the growing stock volume will be converted to above-ground living biomass (including stems, branches, and leaves/needles) using multiplication factors such as the biomass expansion factor (BEF) or the biomass conversion and expansion factor (BCEF), which considers wood density. It should be noted that the guideline provides the values of the conversion factors (BEF) that can be adopted by default (IPCC 2006a; Table 4.5). However, as previous research has shown (Mäkipää et al. 2005), conversion factors obtained from sample measurements of felled model trees vary considerably for various reasons, such as the available tree species, age of forest stands, specificity of forest site conditions, and available sample size. According to various estimates, the standard error of the average value of the biomass conversion and expansion factor used for recalculation of merchantable growing stock volume to aboveground biomass can reach, depending on the tree species, from ±5 to ±20%, and for some tree fractions (e.g. leaves), up to ±40% (Somogyi et al. 2005). This affects the final estimate of the total living biomass of the forests in the national report.

In our calculations, a set of factors differentiated by tree species and age groups for various forest zoning units, corresponding to the current regulatory framework of Russian forestry, were used to convert the growing stock volume to aboveground biomass. Several conversion factors were tested before quantitative estimates of carbon stocks in the living biomass pools were made. Based on an analysis of the factors calculated by various scientific teams, preference was given to the most scientifically sound option proposed by the IIASA (Schepaschenko et al. 2018). IIASA researchers developed and statistically substantiated a set of factors for the main Russian forest species (BCEF), representing the ratio of the weight of individual living biomass fractions (tree stems, branches, and leaves/needles) to the growing stock volume (t d. m. m^{-3}). The total relative error of the BCEF for the living biomass was estimated to be 0.6% (Schepaschenko et al. 2018). In our study, the mentioned set of factors was 1) adapted to forest zoning provided by modern regulatory documents of Russian forestry and 2) incorporated into the computational algorithm using equation [1]. The root-to-shoot ratio (R) in equation [1] also differed for tree species belonging to the different forest zoning units. GIS tools help combine baseline data and conversion factors with forest zoning units (Malysheva et al. 2020). Described algorithm has been implemented and used for calculations of carbon stocks in the living biomass. The uncertainty of the estimates was quantified using standard error (SE). The standard error was calculated as follows:

$$S_{\bar{x}} = \frac{s}{\sqrt{n}} \qquad [2]$$

where:
$S_{\bar{x}}$ – standard error of mean value $\bar{x}$ of the variable x, in our case, the total merchantable growing stock volume per hectare,
n – sample size (number of sample plots),
s – standard deviation of the variable x.

The final uncertainty of the carbon stock in living biomass was obtained as the sum of the uncertainty of the growing stock volume and the BCEF uncertainty.

Among the four commonly used methods for estimating carbon stocks based on forest inventory data (Sun & Liu 2020), the proposed approach can be referred to as a combination of volume-derived and conversion factor continuous methods.

3. Results

The variability of carbon stocks in biomass reflects variations in growing stocks, which are closely related to the differences in climatic conditions and site productivity. Zonal and regional patterns of growing stocks can be clearly observed in the spatial distribution and variabil-

ity of forest-site productivity in Russia. In general, the distribution of the average merchantable growing stock volume corresponded to latitudinal and longitudinal patterns of forest vegetation zoning (Fig. 2). Note that the calculation of the average merchantable growing stocks and average carbon stocks in the living biomass hereafter is per unit area of forest land by forest zone. According to the SFI data, the maximum productivity and average merchantable growing stock volumes were determined for the forests of the coniferous and broadleaved (mixed) vegetation zone and the North Caucasus mountain zone, that is, more than 240 m^3 ha^{-1}. The average merchantable growing stock volumes decrease from its maximum in coniferous and broadleaved (mixed) forests both to the north latitudinal direction up to 89.0 ±6.0 m^3 ha^{-1} in the sub-tundra woodlands and sparse taiga, and to the south latitudinal direction to 62.0 ±5.6 m^3 ha^{-1} in a semi-desert zone of the European-Ural part of Russia. In the Asian part of Russia, the maximum values of the average merchantable growing stock volume according to the amount of 200 m^3 ha^{-1} and more were recorded in the southern taiga and forest-steppe sub-taiga in Central Siberia. The minimum values of the average growing stock were observed in the sub-tundra woodlands and sparse taiga of the Far East and Eastern Siberia from 20.7 ±4.0 m^3 ha^{-1} to 35.0 ±5.0 m^3 ha^{-1} respectively.

The carbon stocks in the aboveground and belowground living biomass pools were estimated for forest lands as a whole as well as for units of forest zoning and administrative divisions.

The latitudinal zonation and the north-south gradient were well traced in the distribution of the mean carbon stocks in living biomass by forest zoning units (Fig. 3).

The average carbon stock in the living biomass increases from 14.3 ±1.6 t C ha^{-1} in the zone of sub-tundra woodlands and sparse taiga in the north to 61.8 ±2.2 t C ha^{-1} in the taiga zone, while reaching an intermediate maximum of 84.6 ±1.4 t C ha^{-1} in the temperate coniferous and broad-leaved forests. South of the coniferous and broad-leaved forest zone, the average carbon stock in the living biomass drops from 71.2 ±1.8 and 62.3 ±2.0 t C ha^{-1} in the forest-steppe and steppe zones, respectively, to a minimum of 22.8 ±2.7 t C ha^{-1} in the semi-desert and desert woodlands. The carbon stock reached its maximum of 119.2 ±4.5 t C ha^{-1} in the forests of North Caucasus Mountains.

The SFI was implemented in the territories of 84 administrative entities of the Russian Federation, namely republics, autonomous okrugs, and regions (oblasts in Russian). Forestland areas, merchantable growing stocks, and total carbon stocks vary considerably among regions. Therefore, we considered the carbon density as

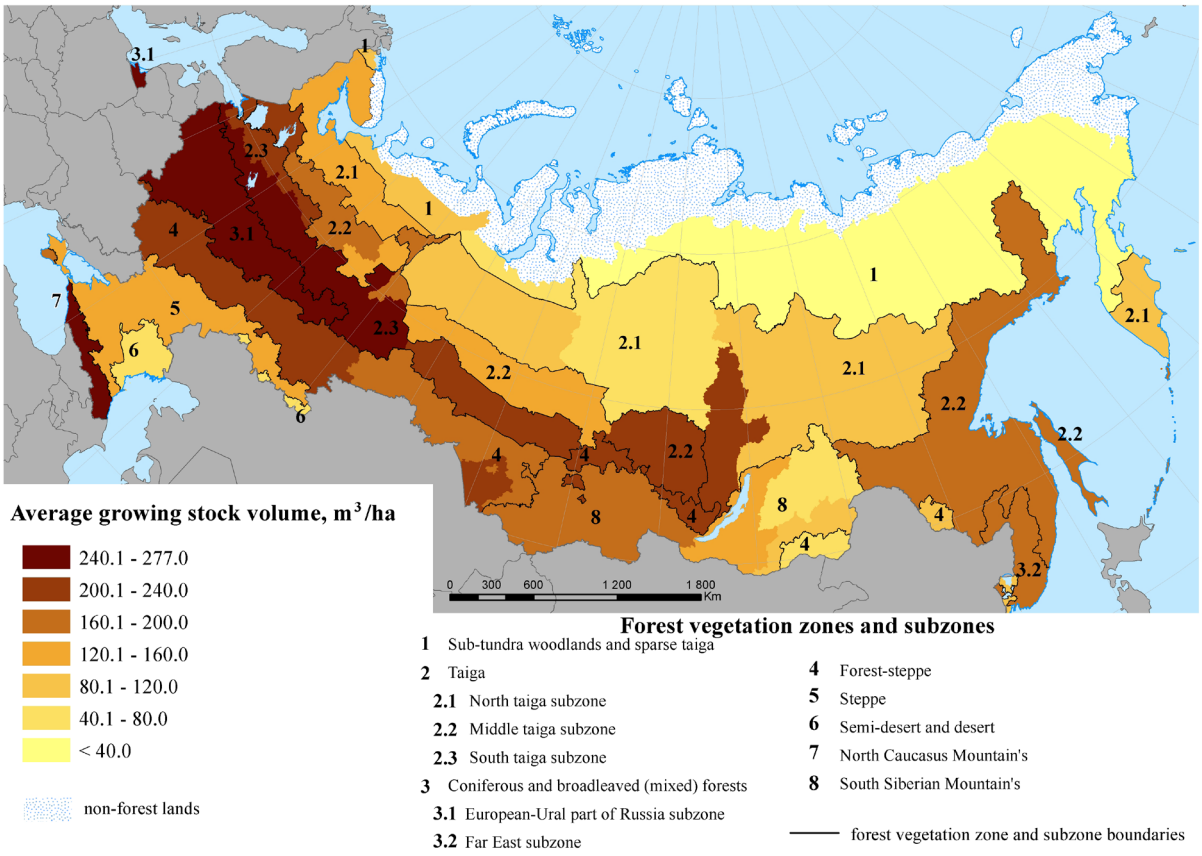


Fig. 2. Spatial distribution of average growing stock volume by forest vegetation zone. The administrative boundaries are shown in accordance with Russian legislation for the year of completion of the SFI first cycle, 2020.

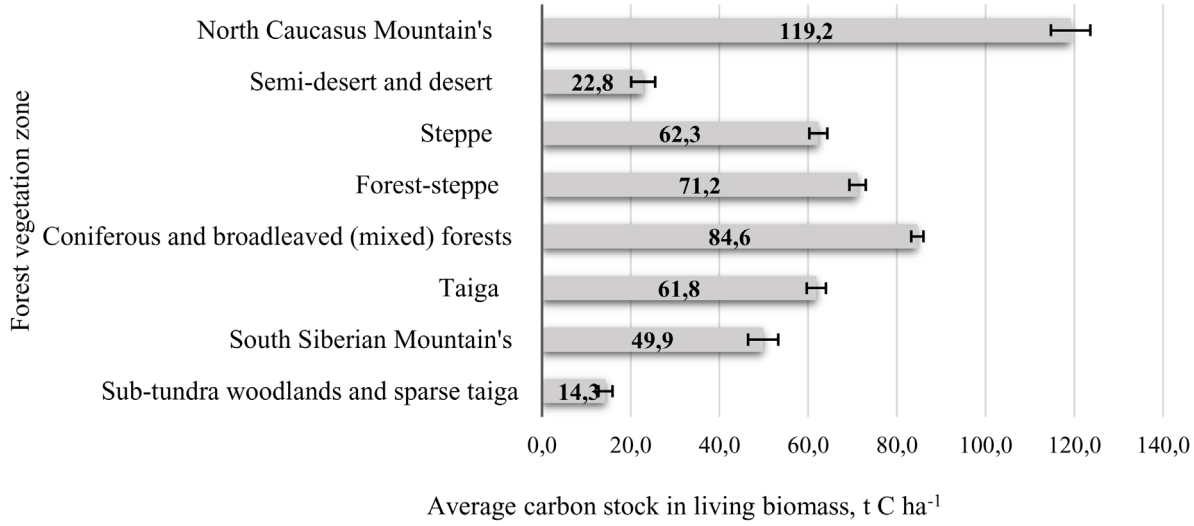


Fig. 3. Average carbon stocks in living biomass by forest vegetation zone. Values represent mean ± standard error.

the amount of carbon in the living biomass per unit area (ha) of forestland. The spatial distribution of the average carbon stocks in the living biomass of administrative units showed differences between regions (Fig. 4).

Due to highly favorable climatic and site-quality conditions, the average carbon stocks in living biomass reached a maximum density of 185.5 (Adygeya Republic) to 212.8 t C ha^{-1} (the Republic of North Ossetia-Alania) in the western part of the North Caucasus area. The minimum density of carbon stocks (5.2 t C ha^{-1}) occurs in the semi-desert and desert woodlands of the Republic of Kalmykia. The climate of this region is arid, with high summer temperatures and minimal precipitation. Typical tree and shrub species in semi-desert woodlands and sparse forests are elm (*Ulmus parvifolia* Jacq.), oak (*Quercus robur* L.), black poplar (*Populus nigra* L.), tamarisk (*Tamarix ramosissima* Ledeb.), and calligonum (*Calligonum aphyllum* [Pall.] Gürke), among others. The Chukotka and Magadan regions in the northeastern part of the Far East rank second in terms of the minimum density of carbon stocks (approximately 11 t C ha^{-1}) (Fig. 4 and Table 1). A harsh climate and widespread perma-

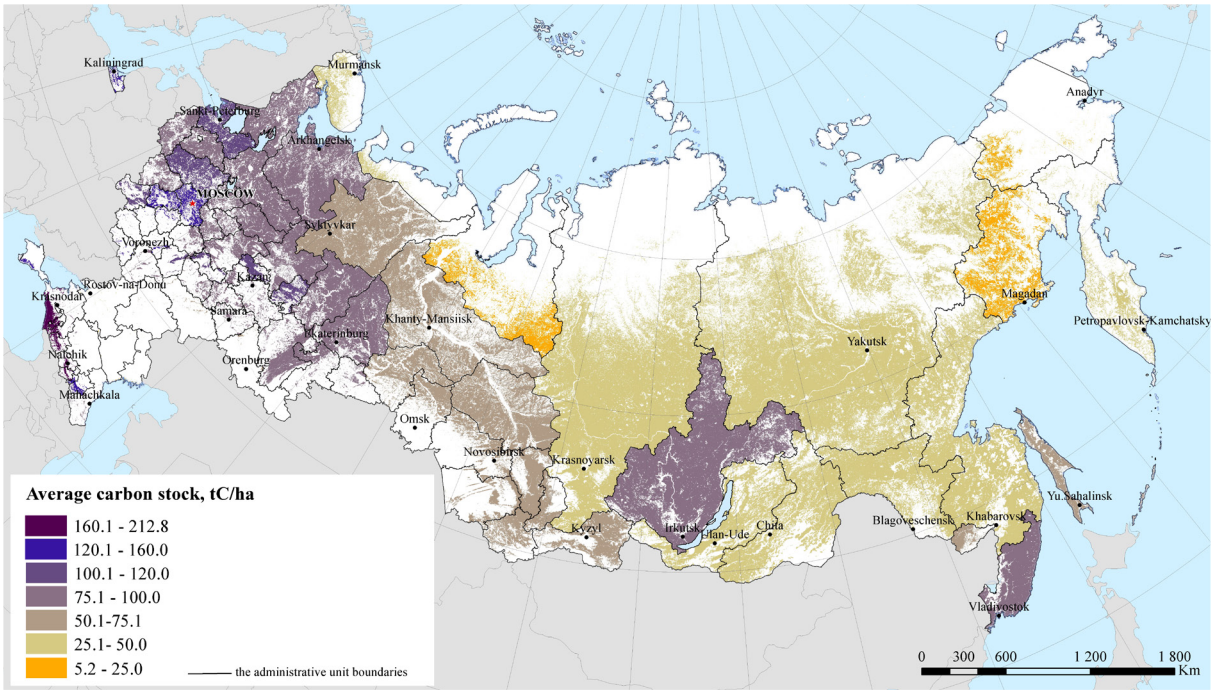


Fig. 4. Spatial distribution of average carbon stock in the living biomass of Russia's forests by administrative units as of 2020*. Note: *The administrative unit boundaries are shown in accordance with Russian legislation for the year of completion of the SFI's first cycle, 2020.

Table 1. Carbon stock in forest living biomass by administrative units of the Russian Federation. Total and average (±SE), million tons C and t C ha^{-1}, respectively.

Administrative unit*	Carbon stock in living biomass		Forest area [million ha]
	Total [million tons C]	Average total [t C ha^{-1}]	
Altay Krai	279 ±23.5	70.1 ±5.9	4.0
Republic of Altay	282 ±31.6	63.3 ±7.1	4.5
Krasnodar Krai	243 ±19.5	163.0 ±13.1	1.5
Krasnoyarsk Krai	5,583 ±383.0	43.2 ±3.0	129.2
Primorsky Krai	1,074 ±84.2	83.0 ±6.5	12.9
Stavropol Krai	9 ±1.7	79.9 ±14.7	0.1
Khabarovsk Krai	2,235 ±100.8	37.7 ±1.7	59.2
Republic of Ingushetia	10 ±2.4	125.8 ±29.6	0.1
Amur Region	1,189 ±49.0	44.7 ±1.8	26.6
Arkhangelsk Region	1,778 ±76.7	77.4 ±3.3	23.0
Astrakhan Region	4 ±0.7	37.2 ±6.6	0.1
Chechen Republic	43 ±6.4	128.4 ±19.1	0.3
Belgorod Region	38 ±2.5	147.2 ±9.8	0.3
Bryansk Region	129 ±9.3	107.7 ±7.8	1.2
Vladimir Region	151 ±9.5	96.5 ±6.1	1.6
Volgograd Region	41 ±6.6	73.5 ±11.8	0.6
Vologda Region	949 ±59.5	91.4 ±5.7	10.4
Voronezh Region	42 ±2.9	95.3 ±6.5	0.4
Jewish Autonomous Oblast	95 ±4.3	55.7 ±2.5	1.7
Nizhny Novgorod Region	335 ±19.7	88.7 ±5.2	3.8
Nenets Autonomous Okrug	8 ±5.0	42.9 ±27.0	0.2
Ivanovo Region	100 ±11.0	95.9 ±10.5	1.0
Irkutsk Region	5,283 ±341.7	79.9 ±5.2	66.1
Kaliningrad Region	37 ±3.0	126.2 ±10.4	0.3
Tver Region	481 ±10.4	101.2 ±2.2	4.8
Kaluga Region	180 ±13.1	130.8 ±9.5	1.4
Kamchatka Krai	556 ±62.1	25.7 ±2.9	21.6
Kemerovo Region-Kuzbass	373 ±24.9	62.3 ±4.2	6.0
Kirov Region	757 ±35.6	95.6 ±4.5	7.9
Kostroma Region	453 ±26.6	98.5 ±5.8	4.6
Chukotka Autonomous Okrug	109 ±70.9	11.2 ±7.3	9.8
Samara Region	59 ±2.9	82.6 ±4.0	0.7
Kurgan Region	131 ±13.9	77.2 ±8.2	1.7
Kursk Region	29 ±2.8	119.0 ±11.4	0.2
Leningrad Region	531 ±16.7	106.8 ±3.3	5.0
Lipetsk Region	27 ±1.5	124.3 ±6.8	0.2
Republic of Crimea	30 ±3.8	121.1 ±15.4	0.2
Magadan Region	305 ±62.2	11.1 ±2.3	27.5
Moscow Region	257 ±24.7	130.0 ±12.5	2.0
Murmansk Region	158 ±9.0	28.8 ±1.6	5.5
Novgorod Region	332 ±15.0	92.2 ±4.2	3.6
Novosibirsk Region	310 ±24.3	63.2 ±5.0	4.9
Omsk Region	270 ±18.5	57.6 ±4.0	4.7
Orenburg Region	41 ±4.0	67.2 ±6.5	0.6
Oryol Region	25 ±2.8	124.6 ±13.7	0.2
Penza Region	89 ±3.5	92.6 ±3.6	1.0
Perm Krai	1,066 ±31.4	90.7 ±2.7	11.8
Pskov Region	216 ±9.7	98.1 ±4.4	2.2
Rostov Region	9 ±0.8	32.6 ±2.9	0.3
Ryazan Region	82 ±3.9	78.1 ±3.7	1.1
Saratov Region	46 ±1.7	70.1 ±2.6	0.7
Sakhalin Region	363 ±24.9	56.0 ±3.8	6.5
Sverdlovsk Region	1,342 ±57.9	99.6 ±4.3	13.5
Smolensk Region	211.2 ±18.2	98.8 ±8.5	2.1
Tambov Region	39 ±2.5	104.6 ±6.8	0.4
Tomsk Region	1,155 ±49.8	59.2 ±2.6	19.5
Tula Region	52 ±4.6	138.2 ±12.2	0.4
Tyumen Region	476 ±24.3	64.4 ±3.3	7.4
Khanty-Mansi Autonomous Okrug	1,624 ±72.3	55.8 ±2.5	29.1
Ulyanovsk Region	94 ±4.6	93.2 ±4.6	1.0
Yamalo-Nenets Autonomous Okrug	318 ±20.3	18.0 ±1.2	17.7
Chelyabinsk Region	223 ±14.8	81.9 ±5.5	2.7
Zabaykalsky Krai	1,274 ±87.4	41.5 ±2.8	30.7
Yaroslavl Region	173 ±11.9	100.5 ±6.9	1.7
Republic of Adygeya	53 ±3.7	185.5 ±12.7	0.3
Republic of Bashkortostan	523 ±20.5	89.9 ±3.5	5.8
Republic of Buryatia	1,068 ±79.5	45.0 ±3.4	23.7
Republic of Dagestan	30.9 ±1.7	82.3 ±4.5	0.4
Kabardino-Balkaria Republic	31.3 ±4.7	165.7 ±25.0	0.2
Republic of Kalmykia	0.1 ±0.1	5.2 ±2.9	0.03
Republic of Karelia	781 ±30.6	79.8 ±3.1	9.8
Komi Republic	1,903 ±108.2	62.1 ±3.5	30.7
Republic of Mari El	140 ±11.0	104.4 ±8.2	1.3
Republic of Mordovia	80 ±6.2	109.5 ±8.6	0.7
Republic of North Ossetia-Alania	41 ±3.2	212.8 ±16.3	0.2
Karachay-Cherkessia Republic	71.9 ±6.3	167.7 ±14.8	0.4
Republic of Tatarstan	106 ±4.2	87.8 ±3.4	1.2
Republic of Tuva	523 ±79.0	58.3 ±8.8	9.0
Udmurt Republic	227 ±33.3	112.8 ±16.6	2.0
Republic of Khakassia	222.5 ±30.1	67.1 ±9.1	3.3
Chuvash Republic	57 ±3.9	94.4 ±6.5	0.6
Republic of Sakha (Yakutia)	6,853.2 ±1,007.4	34.5 ±5.1	198.7
Total	46,920.9 ±404.4	52.1 ±0.5	899.9

Note: *Administrative division units for completing the first SFI cycle in 2020.

frost contributed to the development of resistance to low-temperature sub-tundra trees and shrub vegetation dominated by larch (*Larix dahurica* Turcz. ex Trautv. or *Larix gmelinii* [Rupr.] Kuzen.), dwarf Siberian pine (*Pinus pumila* [Pall.] Regel), willow (*Salix arctica* Pall. and *Salix maximowiczii* Kom.), birch (*Betula cajanderi* Sukaczev), and others.

The maximum values of the total carbon stock in the living biomass were found in the forests of Eastern Siberia and the Far East, namely, in the Republic of Sakha (Yakutia), Krasnoyarsk Krai, and the Irkutsk Region (more than 5×10^9 tons C). The largest areas of forestland in terms of area were located in these administrative units. Mature and over-mature coniferous stands, prevalent in forests, contribute to a significant share of the total merchantable volume. Intensive timber harvesting was concentrated in areas along the Angara River in the Irkutsk region and southeast Krasnoyarsk Krai. In the Republic of Sakha (Yakutia) and the Central and Northern parts of Krasnoyarsk Krai, timber harvesting is limited because of the remoteness of forest areas and lack of adequate infrastructure. Primarily, wildfires cause losses of carbon in living biomass. Among the administrative entities, the Khabarovsk Krai and Komi Republic have the second highest total carbon stocks in living biomass ranging from 1.9×10^9 to more than 2.2×10^9 tons C (Table 1).

We estimated the total carbon stock of aboveground and belowground living biomass in Russia's forests to be $46.9 \pm 0.4 \times 10^9$ tons C, and the average total carbon stock was 52.1 ±0.5 t C ha^{-1}.

The total carbon stocks in the living biomass calculated from the first-cycle SFI data were compared with the results of calculations based on the same methodology

Table 2. Carbon stocks in the living biomass based on the first-cycle SFI data and multi-year (1988 to 2020) carbon stocks based on the SAFF/SFR. Total and average, million tons C and t C ha^{-1}, respectively.

Data source/year	Carbon stock in living biomass [million tons C]			Average carbon stock [t C ha^{-1}]	Total area of forest lands [million ha]
	Above-ground	Below-ground	Total		
First-cycle SFI	37,304.2 ±323.9	9,616.7 ±80.5	46,920.9 ±404.4	52.1 ±0.5	899.9
SAFF and SFR/1988–2020	27,587.6 ±2,111.3	7,228.0 ±553.2	34,815.6 ±2,664.5	39.2 ±3.0	887.4

but on information sources previously used for national reporting under the UNFCCC (Table 2).

Owing to the up-to-date and significant initial growing stock volumes, the living biomass carbon stocks estimated by the SFI data were approximately 35% greater than those estimated by the SFR data. The errors in the total and average carbon stocks based on SFI data were much lower (approximately ±1%). The reason for this is a more accurate estimation of the growing stock volume based on the results of SFI field measurements (±0.35%) compared to the growing stock volume calculated by SFR data, with standard error varying from ±15 to ±30%. Two features of the SAFF/SFR data are noteworthy. First, these data were based on the aggregation of stand-level parameters in forest patches rather than the measurement of trees in the sample plots. Second, the SFR data became irrelevant because the periodicity of forest inventory and planning operations at the forest stand level exceeded the accepted standards (10–15 years), and the limited period of the data for 58.5% of forestland areas exceeded 20 years as of 2020 (Filipchuk et al. 2020).

There are more examples of different estimates of the total carbon stock in the living biomass of Russian forests obtained by various research groups in different years (Table 3).

The published results show that our estimates are generally similar (Table 3) despite the peculiarities of the methods using different data sources and the areas of forest lands included in the calculations. However, the estimates obtained from the SFI data exceed all previously released estimates by 34–59%. The explanation for this is the higher total growing stock volume in Russian forests according to previously reported SFR data. The total carbon in aboveground biomass based on the radar survey published by Santoro et al. (2021) exceeded the estimated value; however, the area in this study was 114 million hectare more than that in our assessments. Furthermore, we compared the study results with estimates of carbon stocks made by researchers from six countries involved in the International Boreal Forest Research Association (IBFRA) project (Högberg et al. 2021). This project focused on the boreal forests of the subarctic zone and part of the temperate zone in the Northern Hemisphere. The circumpolar regions of the Northern Hemisphere include Canada, Russia, Scandinavia (Norway, Sweden, and Finland), and Alaska (United States). According to the FRA FAO 2020, the proportion of boreal forest areas in these countries is 76% in Canada (FRA FAO 2020a), 86% in Russia (FRA FAO 2020f), 93% in Norway (FRA FAO 2020e), 71% in Sweden (FRA FAO 2020g), 98% in Finland (FRA FAO 2020c), and 15% in the USA (FRA FAO 2020h). The boreal belt of the Northern Hemisphere also encompasses forests in northeastern China and northern Japan. However, the share of boreal forests in the total forest area is small in these countries; for example, in China, it is only 7% (FRA FAO 2020b) and in Japan, it is negligible (less than 1%) (FRA FAO 2020d). National reporting of carbon stocks in forest biomass in these countries has traditionally been based on multi-year NFI data. The total and average carbon stocks in the living biomass, according to expert reports from the main boreal countries, as well as our estimates based on the first-cycle SFI data, are presented in Fig. 5.

We estimated the total carbon stock in the living biomass of the Russian boreal forests, according to SFI, at 37.8 ±0.7 × 10^9 tons C with average value of 44.0 ±0.8 t C ha^{-1}. We refer to boreal forests as those located in the following forest vegetation zones: subtundra woodlands and sparse taiga zone, taiga zone, and South Siberian mountainous zone (Fig. 2). The total carbon stock in the boreal forests of Russia is significantly higher than that in other boreal countries because of the significantly larger area occupied by forests. Therefore,

Table 3. Estimates of the total carbon stocks in the living biomass of Russian forests.

Authors/year	Data source/method	Carbon stock in the living biomass [10^9 tons C]	Area [million ha]
Alexeyev & Birdsey 1998	SAFF 1990	29.53	884.09 (forest lands). 771.11 (stocked forest lands)
Isaev & Korovin 1999	SAFF	34.4	no data
Shvidenko et al. 2009	model calculations	34.4	776.1 (stocked forest lands)
Shvidenko & Schepaschenko 2014	model calculations with SFR data	35.1 ±1.5	821.36 (stocked forest lands, including forests on agricultural lands)
Zamolodchikov et al. 2018	SFR data	32.03 ±2.54	785.58 (stocked forest lands)
Santoro et al. 2021	Remote sensing, SAR	64.1*	1,014.2
This study	SFI first-cycle	46.9 ±0.4	899.9 (forest lands)

Note: *Above-ground biomass only.

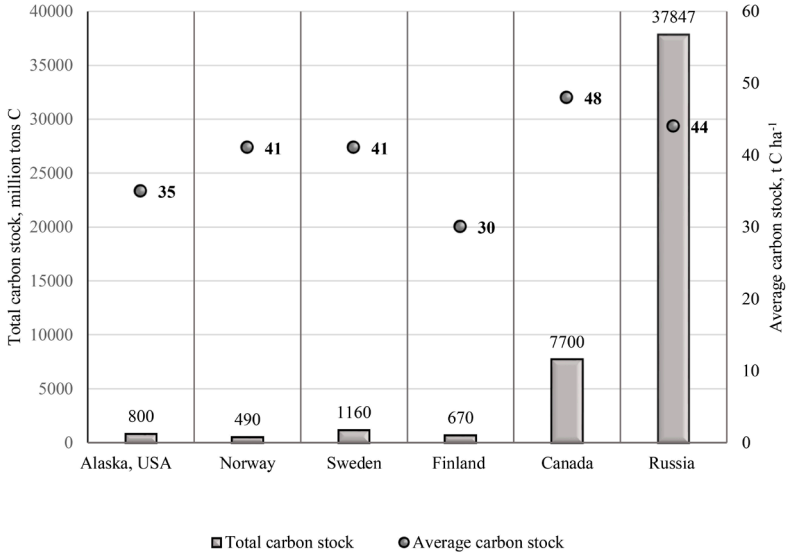


Fig. 5. Carbon stock in forest living biomass in the main boreal countries as of 2018*.
Note: *Data were prepared as part of the Insight Process conducted by a team appointed by the International Boreal Forest Research Association (IBFRA) (Högberg et al. 2021). Data for Alaska were provided for 2009. Data for Canada were provided only for managed forests.

it was reasonable to compare the average values. Overall, the carbon stock in the living biomass of the boreal forests was in the range of 30–48 t C ha^{-1}. In the boreal forests of Scandinavia (Sweden, Norway), the average carbon stock in the living biomass was approximately 41 t C ha^{-1}. The data for the Alaskan and Canadian forests (Fig. 5) can be compared with those of some caveats. For Alaskan forests, the average carbon stock in the living biomass (35 t C ha^{-1}) seems to be somewhat overstated and reflects an expert's opinion, inasmuch as the literature sources, based on NFI data, provide a more realistic value of approximately 24 t C ha^{-1} (Yarie & Billings 2002). The average carbon stock in living biomass was estimated only for Canada's managed forests at 48 t C ha^{-1}. This value is consistent with that received for the boreal forests of Russia (44.0 t C ha^{-1}). The consistency of the values can be explained by the similarity in the age structure of the boreal forests, predominantly conifers, in Canada and Russia. The predominance of forests of older age groups with similar site growth conditions in large areas leads to an increase in the average carbon stock in living biomass. The average stand age in Canadian managed forests is 92 years (Stinson et al. 2011), which is comparable to the average age of Russia's forests estimated at 97 years (Analytical Review 2023). Unlike Canada and Russia, the boreal forests of Scandinavia are intensively managed and have a balanced age structure. Related to this is the lower average carbon stock in the forest biomass of Nordic countries compared with Russia and Canada.

Similar average values of carbon stock in living biomass to ours were obtained for boreal larch- and birch-dominated forests in north-eastern China. The carbon stock in larch trees was assessed as 49.3 t C per unit area and in birch trees as 42.4 t C ha^{-1} (Wei et al. 2013).

4. Discussion

It is necessary to emphasize once again that our study met the general IPCC guidelines. The IPCC encourages any improvements aimed at the quality of greenhouse gas budget estimates, providing verified national data on the impact of the forest sector on the planet's climate system, and obtaining unbiased information on the magnitude of uncertainties in the estimates. It is appropriate to begin the discussion by comparing the carbon stocks in the forest living biomass from this study with those intended for national reporting. To date, the estimation of carbon stocks in Russia's National Inventory Report (NIR) under the UNFCCC for the LULUCF sector has been based on the SFR data. NIR provides information on carbon stocks in managed forests. The area of managed forest lands accepted in the NIR is 666.2 million ha, that is, more than 200 million hectares less than the total area of forestlands in our study, so it is appropriate to compare the average carbon stocks per unit area. According to the NIR, the average carbon stock in the living biomass (above- and below-ground together) of Russia's managed forests amounts to 40.1 t C ha^{-1}, as compared to 52.1 ±0.5 t C ha^{-1} in our study. This means that the average carbon stock in the living biomass, calculated based on SFI data, is 30% higher with less uncertainty (approximately ±1%), whereas the uncertainty of an estimate of the same indicator is more than ±15%, as claimed in the national report (UNFCCC NIR RF 2022). Recognizing the advantages of SFI data in national reporting under UNFCCC obligations, the organization responsible for preparing reports has started to develop a methodology for the use of these data. In 2021, the second cycle of the SFI began in Russia and should be completed by 2030.

Once completed, it is possible to estimate the increment and drain of merchantable stocks in a country's forests. The obtained net increment of growing stock volume will provide an objective assessment of carbon sequestration by the biomass of the Russian forests.

The NFI data are actively used in many countries for national reporting under international obligations. For instance, Pan European indicators for sustainable forest management in the framework of the FOREST EUROPE process Ministerial Conference on the Protection of Forests in Europe include among others the carbon stock in forests. With regard to the State of Europe's Forests 2020 report, the carbon stock in European forests averages 64.0 t C ha^{-1}, but it is much higher at 92.0 t C ha^{-1} in the forests of Central-East Europe (Forest Europe 2020). The amount of carbon fixed in the tree biomass of the Czech forests was 113 t C ha^{-1} (Merganič et al. 2017), which is comparable with our assessments for the forests of the North Caucasus Mountain zone at 119 t C ha^{-1} (Fig. 3). Weighing the results of the carbon stock assessments for Krasnodar Krai forests situated in the North Caucasus Mountain zone presented by Efimov et al. (2022), we can conclude that the total carbon stocks in the aforementioned study are underestimated. The reason for this discrepancy lies in the initial volume of growing stock in the forests of the region used for this assessment. The growing stock of living trees according to the SFI was twice as large as that in the study conducted by Efimov et al. (2022). The mean value of the carbon stock in the living biomass of beech stands, as determined by the NFI in Germany, was 127 t C ha^{-1} (Wellbrock et al. 2017). These results are comparable to those obtained in our study for the most productive forests in the Republic of Ingushetia, situated in the North Caucasus Mountains vegetation zone, that is, 125.8 ±29.6 t C ha^{-1} (Table 1). The dominant tree species in the region, as in the forests of Germany, are broad-leaved: beech (*Fagus orientalis* Lipsky), hornbeam (*Carpinus betulus* L.), and ash (*Fraxinus excelsior* L.). These tree species contribute to approximately 69% of the total merchantable stock volume.

Despite the consistency of the results obtained in our study with the assessments of the expert community, studies with first-cycle SFI data need to be further refined and continued. During the SFI, several indicators were obtained for the first time and were not included in the total estimate of carbon stocks in the living biomass of Russian forests. Such indicators describe the undergrowth, understory, and live ground cover. Although these data do not substantially increase the total estimates of the living biomass stocks, their accounting is of scientific interest. A representative dataset was collected for deadwood in sample plots of the first-cycle SFI. The first summary of deadwood volumes assessed in 27,403 PSPs and its distribution over 15 forest zoning units out of 42 in the whole country has been published (Malysheva et al. 2019). Further research is needed to analyze the representative dataset on deadwood for the country as a whole and the regional distribution of deadwood in greater depth. Dead organic matter represents a significant carbon pool in Russia's predominantly boreal forests. Research is underway to test the methodology for estimating deadwood carbon stocks using first-cycle inventory data. Once the peer review of the methodology for assessing carbon stocks in deadwood is completed, modification of national reporting will follow.

5. Conclusions

This study asserts that the data of direct measurements of quantitative and qualitative characteristics of Russian forests obtained from the first-cycle State Forest Inventory data will be in demand and can improve national reporting on forests in accordance with international commitments.

For the first time, carbon stock in living forest biomass was estimated using inventory data from permanent sample plots for the forestlands of the entire country. The applied methodology was consistent with the recommendations of the IPCC and used a scientifically sound set of conversion factors applicable for estimating tree biomass in Russian forests. The total carbon stock in above- and below-ground living biomass was assessed to be 46.9 ±0.4 × 10^9 tons C and average carbon stock value at 52.1 ±0.5 t C ha^{-1}. Because of the updated and significantly higher growing stock volume, the estimate of carbon stock in living biomass was approximately 35% higher than that previously reported by the SFR data. While the uncertainty of total and average carbon stocks based on SFI data significantly lower (approximately ±1%) as compared to previous ones (±15–30%).

The distribution of the average carbon stock in the living biomass of the Russian forest complies with latitudinal zonation and a north-south gradient. The average carbon stock in the living biomass increases from 14.3 ±1.6 t C ha^{-1} in the zone of sub-tundra woodlands and sparse taiga in the north to 61.8 ±2.2 t C ha^{-1} in the taiga zone, while reaching an intermediate maximum of 84.6 ±1.4 t C ha^{-1} in coniferous and broadleaved (mixed) forests. Heading south along the meridian, the average carbon stock in the living biomass decreases from 71.2 ±1.8 and 62.3 ±2.0 t C ha^{-1} in the forest steppe zone and the steppe zone, respectively, to 22.8 ±2.7 tons C ha^{-1} in the semi-desert and desert zone. The average carbon stock reached its maximum of 119.2 ±4.5 t C ha^{-1} in the forests of North Caucasus Mountains.

Carbon stocks in various forest pools represent a source dataset for subsequent estimates of the annual increment of organic matter accumulated by forest ecosystems and, ultimately, the annual carbon sequestration, that is, the carbon budget input. However, the estimation of organic matter gains or losses in forest ecosystems requires repeated measurements of the param-

eters in the same sample plots. In 2021, the second cycle of the SFI started in Russia and should be finalized by 2030. The information obtained in the second cycle of the SFI provides an answer to the question of the actual potential of Russian forests to absorb atmospheric carbon and accumulate it in forest ecosystems. It is necessary to continue the study and improve the practice of using the data obtained from PSP field measurements, which are unprecedented in terms of territorial coverage, sample size, and accuracy of measured characteristics, to improve the assessment of the carbon budget in Russian forests.

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