Assessment of coarse woody debris stock in Russian forests based on state forest inventory data

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Abstract. The study presents the large-scale assessment relating to the volume of coarse woody debris (CWD), i.e. standing dead trees, downed wood and stumps, in the forests of the Russian Federation. The results of the quantitative estimation of the stocks of snags, downed wood and stumps based on direct field measurements in 27,403 SFI (State Forest Inventory) permanent sample plots that are representative for 15 forest regions. The average total volume of woody detritus is estimated to be 29.22±9.7 m$^3$/ha. The snags makes up 40.3%, downed wood – 55.3%, and stumps – 4.4% of the total CWD. The volume of above- and on-ground woody detritus to average live wood volume ratio is estimated to be 14.6±4.4%, including 5.82±1.8% for standing dead trees, 8.15±3.1% for downed wood and 0.67±0.4% for stumps. The highest volumes of woody detritus on average were found in the forest-steppe zone of European Russia, coniferous and broadleaved forests of the Far East and European Russia, and mountainous forests of South Siberia. The advantages of using the qualitatively new information acquired from SFI materials, for the more exact estimation of the volumes of the above - and on-ground woody detritus have revealed.

1. Introduction
The considerable carbon stocks in the Russian forests fall to share of dead organic matter. Standing dead trees (i.e. snags), downed wood (i.e. logs), stumps, dry branches, and dead roots of trees contribute to the deadwood carbon pool. The aboveground (snags) and on-ground (downed wood, stumps) constituents are often referred to as coarse woody debris (CWD), or woody detritus. The CWD carbon pool is the second largest terrestrial pool after living biomass [1]. In light of this, the quantitative evaluation of woody detritus, as a constituent of the total carbon sequestered by forest ecosystems, takes on great importance.

According to assessments published in national reports under the international climatic conventions [2, 3], the carbon accumulated in woody detritus in Russia averaged 19.8% of the total carbon in the forest biomass in 2017 and 19.5% in 2018. Studies of different research teams gave similar assessments. For instance, according to IIASA research, the carbon accumulated in snags, downed wood and stumps in Russia amounted to approximately 20.0% of the total carbon of the live biomass. The snags account for 37.8%, downed wood – for 30.6%, and dead roots – for 31.6% of the carbon accumulated in the woody detritus [4].

The understanding of the role of this pool and its contribution to the carbon budget of forest ecosystems will require the accumulation of empirical knowledge. The development of methods for estimating organic matter contained in CWD is recognized to be a priority task of reducing the
uncertainty in assessing the carbon stocks in terrestrial ecosystems [5]. The uncertainty in assessing the carbon stocks in downed wood and snags is still appreciably high. For instance, according to the LULUCF Good Practice Guidance [6], the acceptable uncertainty level in assessing the carbon accumulated in snags and downed wood should be ±30% at a nationwide scale. The amount of carbon accumulated in the woody detritus will depend on (1) the volume of timber that became dead or damaged due to negative impacts or mortality in forest stands; (2) the time elapsed after negative impacts; (3) the rate of organic matter decomposition under specific climatic conditions; and (4) carrying out of forest health improvement measures. According to federal figures, the amount of forest sanitary and health improvement measures has declined in the recent years [https://www.fedstat.ru/indicator/43444]. For instance, the proportion of area with forest sanitary and forest health improvement measures implementation relative to the area of dead and damaged forests was 24% in 2013, and then dropped to 16.5% in 2014 and 12% in 2015. Within the same period, according to a federal statistic survey, the proportion of forests perished from fires, unfavorable weather conditions, pests and diseases relative to the area covered by forests grew by 12%, whereas the amount of forest sanitary and forest health improvement measures decreased by 50%. This goes to prove that the scope of the said measures is insufficient, thus resulting in increasing the amounts of downed wood and snags in the forests.

The woody detritus and flows of organic matter related to mortality and decomposition in Russian forests have been studied by small research groups under the pilot projects [7-11]. The scope of their sampling investigation is not too large due to the considerable time of field research over many years. It is challenging to extrapolate the discovered local trends to larger territories, forest vegetation zones, or forest regions. Among the thoroughly documented and published long-term studies dealing with a stock of woody detritus and dead organic matter cycling in Russia’s forest ecosystems it stands to mention the findings obtained by scientists from the Institute of Biology of Komi Scientific Center UB RAS [9], St. Petersburg State Forest Technical University and St. Petersburg Forestry Research Institute [7, 8], and the Sukachev Institute of Forest SB RAS [10, 12].

The accepted method on estimating carbon stocks in woody detritus for National Greenhouse Gas Inventory [13] includes calculation of the mass of coarse woody debris based on the stem timber volume by the State Forest Register data. The average carbon stock of the woody detritus per area in Russia’s managed forests was estimated, based on long-term data, to be 8.2 tons C/ha, or 16.4 tons/ha if calculated with reference to the dried organic matter [13]. In the cited paper, the average annual carbon stocks in deadwood for Russian forests from 1990 to 2004 was estimated to be 4.46 Gt C. The latest National Greenhouse Gas Inventory Report under the UNFCCC and the Kyoto Protocol [2] used the Regional Evaluation of Forest Carbon Budget methodology provides as estimate of 5.23 Gt C.

In many countries, the data derived from national forest inventories are used for estimating the CWD carbon stock at a regional and national scale. For instance, in Sweden the volumes of snags and downed wood have been estimated by using the measurement data at permanent sample plots under the National Forest Inventory program since 1994 [14]. Similarly, the Forest Inventory and Analysis program of the U.S. Forest Service conducts a national inventory of woody material [15, 16]. In a framework of Forest Inventory and Analysis program the volume of both coarse and fine woody detritus have determined by making measurements within 4531 permanent sample plots [16]. The accumulation of State Forest Inventory data in Russia will open the door for their use for estimating carbon stocks sequestered in the CWD pool.

The objective of this research is to summarize and analyze the quantitative characteristics of the coarse woody debris comprised of recent and old snags, downed wood and stumps based on State Forest Inventory data (SFI).

2. Methods and Materials
The State Forest Inventory is a new type of the forest accounting that was brought into use in the Russian Federation in accordance with the forest legislation in 2007 (Article 90 of the Forest Code of the Russian Federation as amended on August 3, 2018 and applied from January 1, 2019). The SFI
operations are carried out by using a common methodology through field measurements in permanent sample plots (PSP). The SFI includes estimating volumes of snags, downed wood and stumps. The obtained data are published in the analytical reviews of the state of forests and their quantitative and qualitative characteristics. Those analytical reviews based on data from the SFI PSP over a period of 2013-2018 provided source data for our research. The characteristics of on- and aboveground constituents of woody detritus were aggregated by 15 forest regions. The forest region corresponds to the stratum or zonal-territorial polygon with homogeneous site-growth conditions and management regimes. The European Russia comprised Karelian Northern Taiga Region, European Northern Taiga Region, Baltic-White Lake Taiga Region, Karelian Taiga Region, Northern Dvina-Vychegda Taiga Region, Western Ural Taiga Region, Southern Taiga Region, Region of Coniferous and Broadleaved Forests, Forest Steppe Region, and Steppe Region (only a part of the Voronezh Oblast). The Asian Russia comprised Middle Ural Taiga Region, Altay-Sayan Mountain Taiga Region, West Siberian Sub-Boreal Forest Steppe Region, Amur-Primorye Region of Coniferous and Broadleaved Forests, and Far Eastern Forest Steppe Region. The total number of permanent sample plots in which field measurements of snags, downed wood and stumps were carried out was 27403.

3. Results and Discussion
The volumes of woody detritus chosen from analytical reviews were subject to statistical processing and summarized by forest vegetation zones/forest regions. Table 1 presents aggregate data relating to average volumes of the on- and aboveground constituents of woody detritus (snags, downed wood, and stumps) by forest vegetation zones/forest regions.

Table 1. Average volumes of woody detritus by forest vegetation zones/forest regions.

| Forest vegetation zone/subzone | Forest region | Average volume per hectare (m$^3$ha$^{-1}$) |
|--------------------------------|--------------|------------------------------------------|
|                                |              | Snags | Downed wood | Stumps | Total |
| Northern Taiga Subzone of European Russia | Karelian Northern Taiga | 9.08±1.7 | 13.10±1.8 | 1.80±0.3 | 23.98±1.9 |
|                                 | European Northern Taiga | 12.00±1.4 | 13.60±1.0 | 1.30±0.1 | 26.90±1.4 |
| Subzone average | | 10.54±1.6 | 13.35±1.4 | 1.55±0.2 | 25.44±1.7 |
| Middle Taiga Subzone of European Russia | Baltic-White Lake | 10.00±0.5 | 22.00±1.4 | 1.60±0.1 | 33.60±6.9 |
|                                 | Karelian Taiga | 11.30±3.0 | 12.70±2.3 | 2.80±0.55 | 26.80±4.9 |
|                                 | Northern Dvina-Vychegda Taiga | 14.00±2.2 | 14.50±1.0 | 1.40±0.15 | 29.90±6.2 |
|                                 | Western Ural Taiga | 8.00±2.0 | 13.80±2.1 | 0.80±0.1 | 22.60±4.6 |
| Subzone average | | 10.83±1.9 | 15.75±1.7 | 1.65±0.2 | 31.84±5.7 |
| Southern Taiga of European Russia (western part)$^a$ | Southern Taiga | 7.75±3.5 | 22.91±5.6 | 1.18±0.58 | 31.84±9.8 |
| Total Taiga Zone of European Russia | | 10.30±3.20 | 16.09±2.1 | 1.55±0.27 | 27.95±5.1 |
| Ural Taiga/Southern Taiga Subzone Zone of Coniferous and Broadleaved Forests in European Russia | Middle Ural Taiga | 15.48±1.3 | 15.50±1.0 | 1.00±0.1 | 31.98±1.2 |
| Zone of Coniferous and Broadleaved Forests in European Russia | Coniferous and Broadleaved Forests | 13.85±9.3 | 20.30±5.9 | 1.1±0.45 | 35.25±7.6 |
| Zone of Coniferous and | Amur-Primorye | 15.10±1.6 | 23.40±1.8 | 1.70±0.2 | 40.20±5.3 |
Broadleaved Forests in the Far East Region of Coniferous and Broadleaved Forests

| Forest Steppe Zone of European Russia | Forest Steppe | 22.72±14.7 | 18.24±4.7 | 1.07±0.4 | 42.03±9.6 |
|--------------------------------------|--------------|------------|----------|---------|-----------|
| West Siberian Forest Steppe Zone     | Sub-Boreal Forest Steppe | 10.41±1.1 | 12.00±1.3 | 0.70±0.1 | 23.11±1.7 |
| Far Eastern Forest Steppe Zone       | Far Eastern Forest Steppe | 5.00±1.0 | 5.30±0.7 | 0.30±0.05 | 10.60±0.9 |
| Steppe Zone of European Russia\(b\) | Steppe       | 12.19±2.2 | 10.46±2.5 | 1.4±0.38 | 24.05±0.91 |
| South Siberian Mountain Zone         | Altay-Sayan Mountain Taiga | 9.47±5.1 | 24.82±10.09 | 1.20±0.27 | 35.49±11.9 |
| Total average                        |              | 11.76±4.21 | 16.17±5.54 | 1.29±0.57 | 29.22±9.7 |

\(a\)The western part of the Southern Taiga Subzone of European Russia covers 47.4% of Novgorod Oblast, 58.5% of Yaroslavl Oblast, 25.3% of Nizhny Novgorod Oblast and 6.4% of Tver Oblast.

\(b\)The Steppe Zone of European Russia covers 26.5% of Voronezh Oblast.

According to the research, the highest average volume of woody detritus per area was found in the forest-steppe zone of European Russia (42.03±9.6 m\(^3\)/ha), and in the zone of coniferous and broadleaved (mixed) forests (35.25±7.6 m\(^3\)/ha), whereas the CWD volume in the taiga zone of European Russia was estimated to be 27.95±5.1 m\(^3\)/ha, i.e. lower than the two above figures. Noteworthy is that the snags account for about 55% of the woody detritus volume in the forest-steppe zone of European Russia. This result casts doubt on the assertions that the higher volumes of woody detritus should be found in natural and climatic zones and forest sites featured by reducing rates of organic matter decomposition [10, 16, 18].

The correlation between woody detritus stocks and forest vegetation zones is shown in [16]. According to data received from permanent sample plots of the Forest Inventory and Analysis program of the U.S. Forest Service, the highest woody detritus carbon stocks (7.78 ton C/ha, or 15.56 tons/ha if calculated with reference to dried organic matter) were found in boreal forests in the north and north-east of the USA, i.e. in ecological zones featured by reducing rates of wood decomposition. A simplified conversion of CWD (snags, downed wood and stumps) volumes shown in Table 1 in mass units, with account of reducing the basic density by 20-25% due to detritus decomposition in the Russia’s taiga forests, results in a similar estimate of 13.6±2.3 tons/ha. However, in the forest steppe zone of European Russia the mass of woody detritus organic matter exceeds the above value in the boreal forests of the USA and amounts to 20.4±4.6 tons/ha (a simplified conversion with account of reducing the basic density by 20-25% due to detritus decomposition). It is very likely that insufficient amount of forest sanitary and forest health improvement measures is the most significant factor influencing the accumulation of woody detritus in the forests of European Russia.

In the Asian part of Russia, the coniferous and broadleaved forests growing in the Amur-Primorye Region of the Far East account for the highest woody detritus volumes (40.2±5.3 m\(^3\)/ha). Somewhat
lower, but comparable (with allowance made for standard deviation) woody detritus volumes (35.49±11.9 m$^3$/ha), were found in the South Siberian mountain zone (Altay-Sayan Mountain Taiga Region). The taiga zone of the Asian Russia includes Middle Ural Taiga Region, in which the average woody detritus volume amounts to 31.98±1.2 m$^3$/ha. It is to be noted that we did not possess sufficiently representative PSP data when dealing with forest vegetation zones of the Asian Russia.

The establishment of the SFI PSP over the best part of the territory is to be completed in 2020. Figure 1 illustrates the spatial distribution of woody detritus by forest regions in which the State Forest Inventory has been completed by the beginning of 2019.

![Figure 1. Spatial distribution of average woody detritus volume by forest regions.](image)

Forest regions: 2 – Northern Taiga Region of European Russia, 3 – Karelian Northern Taiga Region, 4 – Karelian Taiga Region, 5 - Northern Dvina-Vychegda Taiga Region, 6 - Baltic-White Lake Taiga Region, 7 - Southern Taiga Region of European Russia, 8 – Region of Coniferous and Broadleaved (Mixed) Forests of European Russia, 9 - Forest Steppe Region of European Russia, 10 – Steppe Region of European Russia, 15 - Western Ural Taiga Region, 16 - Middle Ural Taiga Region, 22 – West Siberian Sub-Boreal Forest Steppe Region, 28 - Altay-Sayan Mountain Taiga Region, 40 - Amur-Primorye Region of Coniferous and Broadleaved Forests, 41 - Far Eastern Forest Steppe Region.

The comparison of our results with the estimates obtained by other researchers has revealed the following. According to Krankina O et al. [5], the average volume of snags and downed wood in the forests of the Leningrad Oblast amounted to 19 m$^3$/ha, and the woody detritus volume to merchantable volume ratio was estimated at 12.2 % [5]. In our research, we have analyzed samples data obtained from 1,765 SFI permanent sample plots in the forests of the Leningrad Oblast (which are a part of the Karelian Northern Taiga and Baltic-White Lake Forest Regions). Based on the processing of the large bulk of sampling measurements, it was found that the average volume of snags and downed wood
amounted to 28.3 m$^3$/ha while the ratio of woody detritus volume to growing stock of live trees was 10.6%. The total stem wood volume was estimated, by using SFI data, to an accuracy of ±2%. In the mentioned paper [5] the data from 379 permanent sample plots were used. The calculated woody detritus volume to stem wood volume ratio coincides with that calculated for boreal forests in northern Sweden (11%) [19]. This fact can be explained by using similar methods of PSP data collection and data processing, in respect that woody detritus data are collected in Sweden as part of national forest inventory.

In the central part of Russia, we have chosen, for comparison, the SFI data on the volumes of snags and downed wood in the same territorial entities as were considered on paper [5]. This was a representative sampling from 8,280 SFI PSP in RF territorial entities. According to our research, the total average volume of snags and downed wood amounted to 35.7±10.3 m$^3$/ha. The woody detritus volume to stem wood volume ratio was estimated to be 14.03±4.3%. In their turn, Krankina O et al. [5] found that the above indices were 16 m$^3$/ha and 10.3%, respectively. These data indicate that the values of woody detritus volume to stem wood volume ratio (with allowance made for standard deviation) are in line in both studies, whereas we received the appreciably higher value of the total average volume of snags and downed wood. Other than we estimated the stem wood value more accurately (±2%), this can be explained by the accumulation of snags and downed wood in the forests of the central part of Russia in recent years as a result of forest mortality caused by pests and diseases and inadequate amount of sanitary and forest health improvement measures. This conclusion is supported by the findings of the Review of Sanitary and Forest Health in the Russian Federation in 2017 [20].

4. Conclusion

Based on the field measurements carried out on 27,403 SFI permanent sample plots (PSP) within 15 forest regions of the Russian Federation, the second-to-none large-scale estimates of the volumes of the above- and on-ground woody detritus have been obtained. The total average CWD volume is estimated to be 29.22±9.7 m$^3$/ha. The snags makes up 40.3%, downed wood – 55.3%, and stumps – 4.4% of the total CWD volume. The average on- and above-ground woody detritus volume to average stem wood volume ratio is estimated to be 14.6±4.4%, including 5.82±1.8% for snags, 8.15±3.1% for downed wood and 0.67±0.4% for stumps.

The highest average volumes of woody detritus were discovered in the forest-steppe zone of European Russia, coniferous and broadleaved forests of the Far East and European Russia, and mountainous forests of South Siberia rather than in ecological zones featured by reducing rates of organic matter decomposition. Our research findings cast doubt on the assertion that zonal characteristics of spatial distribution of the woody detritus volumes will prevail over other factors. It is very likely that the amount of forest sanitary and health improvement measures, forest disturbance levels and available stand age group will influence the accumulation of woody detritus much more than the type of vegetation and other environmental variables.

Within 15 forest regions, located mainly in the European Russia, our research revealed that the woody detritus volume to stem wood volume ratio (with allowance made for standard deviation) amounts to 14.6±4.4% that is close to the CWD carbon stock to the live biomass carbon stock ratio mentioned in Russia’s national reports to the international climate conventions (19.5% as of 2018) [2, 3] and cited in the research paper [4]. Our conclusions are of a preliminary nature because of the analytical estimations of CWD volumes being limited to SFI PSP measurements in only 15 (of the total 41) forest regions in which SFI has been completed. The obtained results let us hope that the representative PSP field data to be collected under unified methods after the completion of SFI cycle will make it possible to obtain unbiased and reliable quantitative estimates of the woody detritus carbon stocks. The establishment of the SFI PSP over the best part of the Asian territory of Russia is to be completed in 2020. We can expect that the proposed sources of data and direct measurements rather than any model assessments will fundamentally improve climate reports of the Russian Federation to the UN FCCC related to land use, land-use change and forestry under the Paris Agreement.
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