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A Modelling System for Dead Wood Assessment in the Forests of Northern Eurasia

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Abstract: Dead wood, including coarse woody debris, CWD, and fine woody debris, FWD, plays a substantial role in forest ecosystem functioning. However, the amount and dynamics of dead wood in the forests of Northern Eurasia are poorly understood. The aim of this study was to develop a spatially distributed modelling system (limited to the territories of the former Soviet Union) to assess the amount and structure of dead wood by its components (including snags, logs, stumps, and the dry branches of living trees) based on the most comprehensive database of field measurements to date. The system is intended to be used to assess the dead wood volume and the amount of dead wood in carbon units as part of the carbon budget calculation of forests at different scales. It is presented using multi-dimensional regression equations of dead wood expansion factors (DWEF)—the ratio of the dead wood component volume to the growing stock volume of the stands. The system can be also used for the accounting of dead wood stock and its dynamics in national greenhouse gas inventories and UNFCCC reporting. The system's accuracy is satisfactory for the average level of disturbance regimes but it may require corrections for regions with accelerated disturbance regimes.

Keywords: boreal and temperate forests; Northern Eurasia; coarse woody debris; expansion factors; snags; logs; stumps; dead branches; carbon stock

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1. Introduction

Dead wood is an important component of forest ecosystems. It generates a carbon pool [1,2] with a residence time from decades to centuries, especially for the snags in cold climates [3–5]. Fallen dead wood increases the moisture of the soil surface [6] and the nutrient availability [7,8], as well as maintaining biodiversity [9,10], as 20%–40% of organisms in forest ecosystems depend on dead wood [11] during their lifecycle. In boreal and temperate forest ecosystems, the amount and dynamics of dead wood significantly affect the carbon budget, comprising 10%–15% of the ecosystem heterotrophic respiration [12]. Moreover, dead wood provides important regulating and supporting [13,14] ecosystem services, as well as provisioning services by supplying wood for the forest industry and local consumption, and serves as a source of energy for the rural population (e.g., for cooking and heating) [15,16]. On the other hand, dead wood may increase the fire risk and the severity of wildfires, particularly in dry climates [17–19], and host dangerous pests [20,21], e.g., bark beetles [22] and aggressive fungi (such as *Armillaria ostoyae* (Romagnesi) Herink [23] or heart rot fungi [24]).

The amount, spatial distribution and temporal dynamics of dead wood in the Northern Eurasian (NE) forests are poorly quantified. The forest inventory that took place in the countries of the former Soviet Union has accounted for the volume of snags and logs in each inventoried stand. However, (1) these mostly visual evaluations are very rough; (2) they do not include all the components of dead wood; (3) they are biased because the minimum threshold for the amount of snags and logs in the inventory varies from 5 to 30 m^3 ha^{-1} depending upon the region and the forest management category; (4) as a rule, they do not account for the final stages of decomposition; and (5) the aggregated data from dead wood inventories have not been published historically, but only presented in forest inventory reports by individual forest inventory enterprises. Overall, this has led to the substantial underestimation of coarse woody debris (CWD) in the forest inventory. For instance, the control inventory of CWD in the Leningrad region (covering mostly the zone of southern taiga in European Russia) showed that the forest inventory accounted for only 9% of the actual dead wood stock [25].

The publications on this topic contain mostly approximated national-level estimates, which have been based on simplified approaches applied to aggregated data from the forest inventory [26–30]. However, a considerable number of regional and national studies of the region considered here, including the overall results from the first stage of the first cycle of the State (National) forest inventory (NFI) in Russia (2007–2020), have been published more recently, e.g., [31–33].

The approaches to define and classify dead wood vary both nationally and internationally. Harmon et al. [34] accounted for all components of CWD, including dead coarse roots, with a diameter exceeding 2.5 cm. After this study was undertaken, North American scientists then recommended separating dead wood into fine woody debris (FWD) limited by 1 cm at the thin end, and CWD with a corresponding diameter > 10 cm; for pieces thinner than 1 cm, the term fine litter has been suggested [35]. Currently, the National Forest Inventory and Analysis System in the USA accounts for CWD of d > 7.62 cm, and FWD from 0.01 to 7.62 cm [36]. In many national studies, the threshold diameter at the thick end varies from 1 to 30 cm, although more often from 5–8 cm [37,38]). In the countries of the former Soviet Union, various forest inventory manuals list different requirements, generally in the range from 6 to 10 cm [25,39]. The first cycle of the NFI in Russia accounts for snags (starting from 6 cm DBH), logs (diameter of 6 cm at the thin end and a length of more than 0.5 m) and stumps (accounted for from 12 cm in diameter) [40]. According to the Russian NFI data, the mean volumes of snags, logs and stumps are 11, 16 and 0.96 m^3 ha^{-1}, respectively. The CWD to growing stock volume (GSV) ratio is 0.21 [41].

In this study, we consider deadwood by keeping the traditional term Coarse Woody Debris for on-ground and above-ground dead wood with a diameter at the thin end equal to or larger than 1 cm. The relevance of such a size is explained by the following reasons: (1) in the majority of ecological studies, on-ground dead woody residuals with $d \leq 1.0$ cm are considered as part of the soil (i.e., top soil organic layer or litter); and (2) due to the availability of large territories (above 200 million ha) of low productive forests of forest tundra and northern taiga zones with an average height of 5–10 m and an average diameter of 10–16 cm. In this classification, CWD consists of snags (standing and leaning dead trees and their parts with a height $\geq$ 1.3 m), stumps (height < 1.3 m), logs (dead wood lying on the ground) and dead branches of living trees, which provides a complete account of dead wood in forest ecosystems.

In this study, we attempted to build a modelling system to account for dead wood in NE forests based on the most comprehensive database of field measurements to date. The study region includes all independent countries that have formed in the territories of the former Soviet Union.

Brief Overview of State of the Art

The stock and structure of CWD depend on forest land cover classes (i.e., stocked forests, open woodlands, burnt areas, dead stands, harvested areas); the geographical location; the level of productivity; the extent and severity of natural and human-induced disturbances; and the time since the last disturbance occurred. Major drivers, which define the amount of CWD in forested areas (i.e., "forest" based on national definitions) are the tree species composition, the age and age structure type of the tree stands, the site conditions, the slope and exposure, the history of previous non-stand replacing disturbances and the intensity of the forest management [42,43]. The dynamics of the stocks of CWD on unmanaged lands are variable across seasonal, annual and successional scales [34,44,45].

The three major processes defining the amount and dynamics of CWD in forest ecosystems are natural tree mortality, disturbances and decomposition. The CWD pool is supplied by natural processes including tree mortality, the loss of branches during tree growth, and stand development, as well as disturbances (e.g., pests, fire, harvests). The loss of the CWD pool is caused by wood decomposition and disturbances, such as fire and forest management (e.g., salvage logging, collecting firewood, etc.).

The variability in tree mortality is diverse in NE forests including complex interactions of natural, pathological and mechanical types of mortality. The highest mortality level is observed in the unmanaged remote territories of Russian Asia and the areas in the southern part of the forest zone closest to the Mid-latitude ecotone. This depends upon the complex interactions of the regional specificity of the forest cover (i.e., age, species composition, productivity, level of forest transformation, vitality) under the impacts of diverse catastrophic and non-catastrophic agents [26,34,46–49]. Based on our estimates, the tree mortality in NE forests in the years around 2010 was approximately 46% of the gross growth.

Disturbances play two distinct roles. On the one hand, they promote the accumulation of CWD because of significant after-disturbance mortality (i.e., up to 50%–60% of the initial growing stock after non stand-replacing steady ground fires [50]). On the other hand, wildfire consumes a substantial part of the CWD. On average, steady ground fires consume 20%–60% of the on-ground forest fuel (including litter and logs) in boreal forests [6,51].

One of the most influential factors regulating the process of accumulation and the dynamics of CWD is the level of forest management intensity where the largest differences are observed between managed and unmanaged forests. On average, the stock of CWD in the intensively managed forests of temperate and boreal zones is in the range of 5–7 m^3 ha^{-1} to 10–14 m^3 ha^{-1}, respectively [52–55]. The nation-wide average volume of CWD in Sweden in managed mature (9.3 m^3 ha^{-1}) and overmature (12.2 m^3 ha^{-1}) forests was substantially lower than in key habitats of unmanaged woodland (with an average of 19.5 m^3 ha^{-1} and a maximum in boreal regions ranging from 24.8–30.6 m^3 ha^{-1}) [56]. The intensity of management also substantially impacts the structure of CWD: on average, snag comprises a relatively small part (10%–20%) of CWD in managed forests versus 35%–45% in unmanaged [26,54,57,58]. The amount of CWD in northern unmanaged forests mainly depends on the productivity of forests and the history of recent disturbances [59].

Even with the absence of recent severe disturbances, the stock of CWD in the productive forests of the temperate and boreal zones in NE can be very high. From a number of surveys, it varied from 50 to 150 m^3 ha^{-1}, and was sometimes substantially higher [37,60,61]. The variability of the stock of CWD can be very high even within homogeneous regions and forest formations. For instance, the average stock of CWD that we measured in 17 sample plots in mature unevenly aged dark coniferous forests on Sakhalin Island, which is dominated by *Picea ajanensis* Fisch. ex Carrière-*Abies sachalinensis* (F. Schmidt) Mast., was 51.2 m^3 ha^{-1}, and the coefficient of variation of the amount of dead wood on these sample plots was 29.6%. The average stock of snags and logs from 61 sample plots in mature undisturbed forests of *Picea ajanensis* on Kamchatka peninsula was estimated to be 56.8 m^3 ha^{-1}, or 25.5% of the growing stock volume; the variation of both indicators was around 45% [62]. However, two series of sample plots established in similar landscapes of the multi-species Siberian pine-broadleaved forests of the Russian Far East, which differs by protective status (national park vs. exploitable forests) and the accessibility of the forests, had a volume of logs in protective forests that was 3.6 times higher and a wood density of 0.168 vs. 0.222 Mg m^{-3} [44,63].

Severely damaged forests can accumulate a huge amount of CWD. For instance, the amount of CWD in the dark coniferous forests of the low reaches of the Amur River (dominated by *Picea ajanensis* and *Abies nephrolepis* Max.), which have been affected by intensive dryness processes [64], as well as in forests dominated by Siberian pine (*Pinus sibirica* Du Tour) in Krasnoyarsk Kray, which are affected by outbreaks of Siberian moth (*Dendrolimus superans sibiricus* Chetv.), are made up of 180 to 350 m^3 ha^{-1} of CWD [6,65]. A high amount of the CWD is in young forest stands of the taiga zone, which are regenerated after stand-replacing fires [66].

The dynamics of the amount of CWD in unmanaged stands varies substantially. Natural forests regenerated after natural disturbances follow a "U-shaped" successional pattern of CWD dynamics [67–69], whereas in planted forests, where the initial stock of CWD is small, the increase of CWD corresponds to a J-curve [57,70,71].

The average life span of snags (after trees die) also varies greatly. For example, for stands of Norway spruce (*Picea abies* (L.) Karst.) in Scandinavia, 80% of snags fall down after 20 to 34 years, and the remaining 20% from 38 to 53 years [72]. The forest stands of Siberian pine (*Pinus sibirica*) in the Altay mountains, which burned in 1914, were studied in 1961. The average stock of snags in five stands was estimated to be 186 m^3 ha^{-1} while the growing stock of the undisturbed stands was 321 m^3 ha^{-1}, i.e., about 58% of the initial growing stock remained as snags during the 50 year period after the fire; the average percentage of trees that were not damaged by decay was 60% on burned areas and 90% in undamaged stands [73]. According to our estimates, about 20% of the snags remained standing in the forest tundra of Yakutia on permafrost in a stand killed by fire that was dated around the 1880s. However, the 10-year average transition period of snags into logs was reported for major forest forming species in the middle taiga of the Leningrad region [70,74].

For northern (boreal) forest, the "age" of snags has been estimated to be up to 150 years for spruce and up to 230 years for larch [3].

Because the process of the falling of snags is stochastic, the half-time period (i.e., when the probability of a snag falling down is equal to the probability that it will remain standing) is a relevant indicator. From our observations in different regions of NE, this period varies from 15 to 30 years in southern taiga to about 50 to 70 years at the northern tree line of NE, although its variability is high even within homogeneous forest regions. Other estimates for the northern part of the Siberian boreal forests are similar—20 to 40 years for Siberian pine, up to 50 years for spruce, and 40 to 150 years for larch (e.g., [75,76]). A number of studies outside Russia report estimates closer to the lower limit of the estimates provided above (see also [72,77]). However, the time period when the probability that snags remain standing is less than 0.01 was estimated to be 70 to 75 years in *Picea mariana* (Mill.) Britton, Sterns & Poggenb. and more than 115 to 120 years in the *Abies balsamea* (L.) Mill. forests of Quebec [78].

2. Materials and Methods

In large CWD inventories, sample plot measurements are usually upscaled based on the aggregated forest inventory data [26,34,79]. However, for the NE region, this method has substantial shortcomings due to the high, but poorly studied, variability in the spatial distribution of CWD, which can reach 10 to 15 times the estimates, and sometimes even up to two orders of magnitude greater [80]. Alternatively, different empirical models, e.g., based on the ratio between the volume or mass of CWD to the growing stock volume (GSV) of stands (i.e., dead wood expansion factors), can be used [25]. This approach requires relevant "regionalization" and might not account for the impacts of the intensity (or absence) of forest management or disturbances in individual stands.

The experimental material for this study is represented by a database [81], which includes the results of field measurements on 2100 sample plots established in the frame of different projects, and measurements from 7300 sample plots from the first cycle (2007–2020) of the NFI. The NFI data were combined in homogeneous clusters due to the high variability of the measured indicators on individual, small by size (0.05 ha), sample plots. The final clusters, of which averages have been directly used in the modelling, were formed in the following order: bioclimatic zone, species (group of species), site index and age class (20 year). The site index is presented by a mean height at a base age by groups of species (see Table A1).

Overall, 3805 records have been used for modelling the volume of snags and 3201—for logs. Different auxiliary sources of information were used in order to clarify the geographical and biometric diversity of the NE forests and were compared with the models developed here: (1) the available regional empirical coefficients and models e.g., [25,70,74,79,82]; (2) the results of the inventory of snags and logs in volume units on over 2000 sample plots established by the Inventory and Planning System (*lesoustroystvo*) in different regions of the country; and (3) aggregated data for ca. 350 individual forest enterprises (distributed over the entirety of Russia) extracted from the regional inventory reports. The accuracy of these auxiliary data has not been estimated. The database is available here [81].

The modeling was performed separately by regions depending on the available amount of experimental data and the statistical significance of the difference between regional averages. The models have been developed by bioclimatic zones, which were aggregated as follows: (1) forest tundra and northern taiga; (2) middle taiga; (3) southern taiga; (4) temperate forests, forest steppe and steppe; as well as by three large longitudinal sectors: (1) the East-European part of the study region, (2) Siberia and (3) the Far East. The bioclimatic zones of the geographical regions of Siberia (West, Central and Eastern) were combined based on statistical analysis of the empirical data.

The tree species and groups of dominant species included: (1) Pine (basically *Pinus sylvestris L.*); (2) Larch (*Larix* spp., mostly *L. sibirica* Ledeb., *L. gmelinii* (Rupr.) Kuzen. and *L. cajanderi* Mayr.; (3) Spruce (*Picea* spp., mostly *P. obovata* Ledeb., *P. abies, P. ajanensis*) and Fir (*Abies* spp., mainly, *A. sibirica* Ledeb.); (4) Siberian Pine (*Pinus sibirica*) in Siberia and *P. koraiensis* Siebold & Zucc. in the Far East); (5) Oak of seed origin (*Quercus robur* L.) in the European part of the study area and *Q. mongolica* Fisch. ex Ledeb. in the Far East); (6) Oak of vegetative origin (as outlined in 5); (7) Other hardwood species: Ash (*Fraxinus excelsior* L.) Beech (*Fagus orientalis* Lipsky), Hornbeam (*Carpinus betulus* L.), Maple (*Acer* ssp.); (8) Stone birch and other hard wood species (basically *Betula ermanii* Chamisso and other Far-Eastern hard wood birches); (9) Softwood birches (basically, *Betula pendula* Roth and *B. pubescens* Ehrh.); (10) Aspen (*Populus tremula* L.); (11) Other softwood species (basically, *Alnus glutinosa* (L.) Gaertn. and *A. incana* (L.) Moench); and (12) Siberian dwarf pine (*P. pumila* (Pall.) Regel). Overall, these species cover more than 98% of the NE forests.

The statistical analysis of the data showed the statistically significant dependence of the dead wood expansion factors (DWEF) on the age and site index of the forest stands within the geographical units used (Figure 1).

According to the system developed here, the assessment is provided as follows: (1) estimates of the amount of CWD volume by components by regression equations, (2) assessment of the dry mass by application of a matrix of wood density, and (3) estimates of the amount of dead wood in carbon units by application of the values of the carbon fraction in the dry mass.

The CWD data from the sample plots were used to fit a linear regression model with the log transformation of the response to the data in the following form [83]:

$$logit\left(R_{fr}\right) = log\left(\frac{R_{fr}}{1-R_{fr}}\right) = a_0 + a_1 logA + a_2 log\mathrm{SI} + a_3 A + \varepsilon, \quad (1)$$

$$R_{fr} = \frac{exp\left(logit\left(R_{fr}\right)\right)}{1+exp\left(logit\left(R_{fr}\right)\right)}, \quad (2)$$

where R_{fr} is the ratio of the volume of a CWD fraction *fr* (snags, logs, stumps, dead branches of living trees) to the GSV (conversion coefficient, or dead wood expansion factors); *A* is the average stand age, in years; SI is the site index, which reflects the quality of a site and is expressed as the average height (m) of a mature forest (50 years old for birch, aspen and other deciduous soft wood species, and 100 years old for other species); and a_0–a_3 are the model parameters. The residual ε is commonly assumed to have a Gaussian distribution with a zero mean and constant variance.

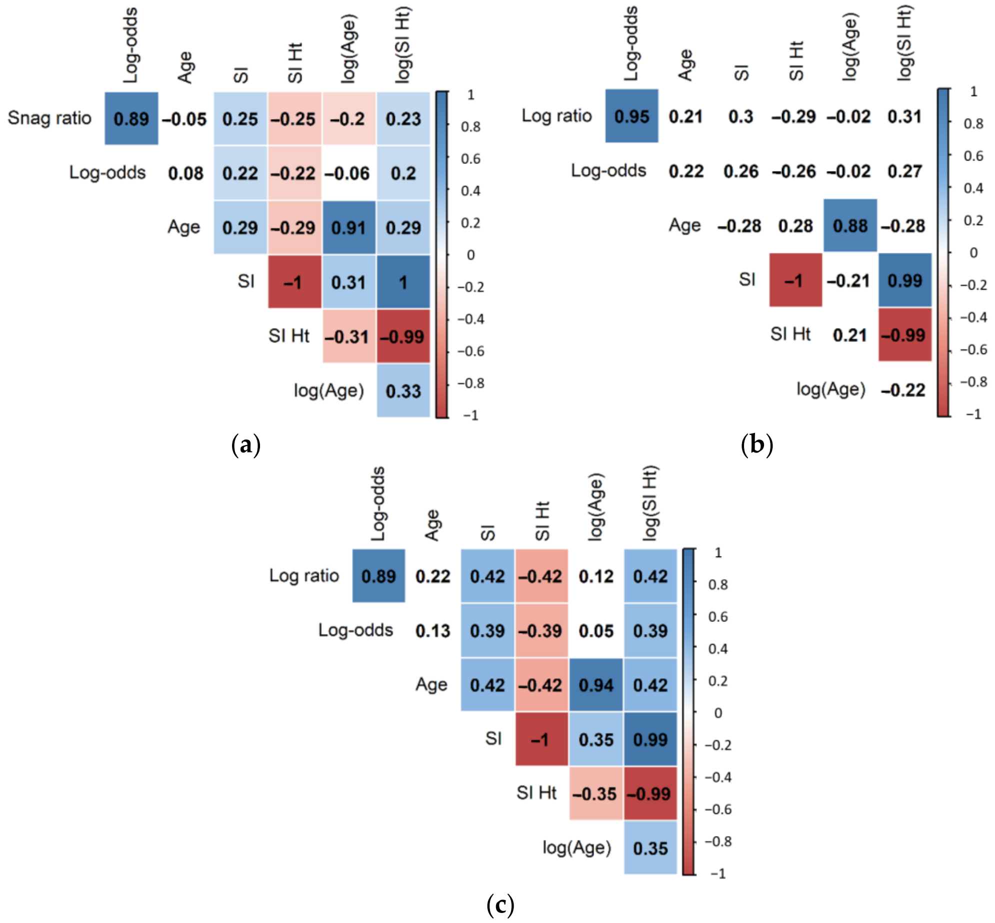


Figure 1. Examples of correlation matrices of the variables used: (**a**) pine, snags, European Russia, combined for forest tundra and northern taiga zones; (**b**) logs, larch, middle taiga, Siberia; (**c**) birch, logs, combined for Siberia and Far East. SI—site index, SIHt—site index expressed by average tree height at mature stage (see Table A1).

Dead Wood Density (Specific Gravity)

The conversion of CWD volume to dry mass and carbon requires the knowledge of both wood density (specific gravity) and the content of carbon in the dry matter of the dead wood. Wood density is defined as the ratio between an oven-dry CWD mass to a volume under moisture at the limit of hygroscopicity. The experimental data include classifications of CWD by stages or classes of decay (decomposition), with a number of grades usually from 3 to 5, and rarely 7 [55,66,84]. The density of dead wood decreases during the process of decomposition.

Numerous studies have reported rather similar wood density losses by decay classes for individual tree species or groups of species by bioclimatic zones. The reported specific gravity of the 1st class of decay of CWD is usually very close to that of healthy wood, sometimes slightly more; for the 2nd class—on average, it varies between 80%–85% of the initial mass, e.g., for Siberian taiga coniferous forests—from 65%–75% (larch) to 94% (pine).

A substantial decrease in the specific gravity is observed for the 3rd class—e.g., from 48% for aspen, 45%–55% for larch to 68% for fir, and 76% for Siberian pine [25,85,86].

Considering the rather complicated picture of geographical and tree species diversity of wood density by classes of decomposition, we present some typical examples here. In the Eastern European middle taiga, the reduction of specific gravity from the 2nd to the 5th decay class of (a percentage of specific gravity of the 1st class) was estimated to be 85:66:45:20 for spruce; 80:59:36:11 for birch, and 69:56:37:13 for aspen [87], and the specific gravity for the 1st class in this study was 0.425 Mg m^{-3} for spruce, 0.461 for birch and 0.415 for aspen. In the neighboring southern taiga zone of the same region, the specific gravity of the 1st class of pine was 0.384, spruce was 0.347 and birch was 0.280, and the relative density of other classes was, respectively, 83:61:29:28; 89:60:32 (no data for the 5th class); and 92:49:26:20 [46].

In the pine forests of the Middle Volga basin (zone of mixed forests with domination of coniferous), such a ratio was 80:54:34 (four decomposition classes were used), and specific gravity by the classes (Mg m^{-3}) constituted 0.480, 0.384, 0.257 and 0.165, respectively [88]. For Korean pine (*Pinus koraiensis*) in the monsoon climate of the south of the Russian Far East, the ratio was 93:73:60:42 [63].

The East Near Baikal density of logs of *Pinus sylvestris* by decay classes were 0.468 ± 0.020; 0.430 ± 0.017; 0.310 ± 0.027 (1–3 classes) and *Abies sibirica* 0.525 ± 0.20, 0.376 ± 0.024, 0.273 ± 0.013 (1–3 class) [89].

Major hardwood deciduous species of NE have similar dynamics of density by classes of decay, e.g., 88:69:50:37 for logs of *Quercus mongolica* and *Ulmus glabra* Huds. in the southern Far East (density of the 1st class of decay was 0.50 Mg m^{-3} for both species) [63].

The density loss patterns across decay classes of individual species, belonging to the same genera, but with a geographically separated growing area (e.g., *P. sibirica* and *P. koraiensis*, or *Quercus robur* and *Q. mongolica*) is similar within a genera for major forest forming species [3,63]. In aggregated estimates, the density of logs for Belarus was reported to be 0.3 Mg m^{-3} or 0.15 Mg C m^{-3} [90].

Despite the qualitative character of identifying decay classes in different classifications, a number of studies have reported neither significant biases of the assessment results using different classifications of CWD [91] nor substantial errors as a result of the qualitative definition of the decay classes.

Overall, the ratio of the stock of logs to snags in NE forests varies across a rather wide range—from 1:3 to 1:1, e.g., [26]. However, due to the substantial alteration of disturbance regimes in recent decades in Northern Asia and the lack of silvicultural treatments over large territories, the share of snags in the total amount of dead wood is growing.

Whereas many studies report rather consistent results on the reduction of the wood specific gravity of logs for different decay classes within individual species or groups of similar species [92,93], the data for snags are more dependent on bioclimatic zones [3,4,70]. The decay process of snags is species-, site- and geographical location-specific and may be very slow in harsh climatic conditions. For instance, the reduction in the decay of the specific gravity of the wood of snags for spruce and larch in the forest tundra of Central Siberia is substantial only after 80 to 100 years, and the rate of decomposition of the wood from snags is one to two orders lower than that of logs [3]. A low decomposition rate has also been reported for postfire charred snags [6,94].

3. Results

3.1. Modeling the Dead Wood Expansion Factors (DWEF)

The system developed here in the form of regression Equation (2) contains 88 regional models by tree species and aggregations of ecological regions, and large sectoral regions. The system includes 41 models for snags, 41 for logs and 3 aggregated models of DWEF for the stumps and dry branches of live trees (Tables A1–A5). The aggregation of the models was partially based on the lack of statistical significance of differences between average

DWEFs of the major components of CWD of neighboring ecoregions. Some examples of model behavior are presented in Figures 2–6.

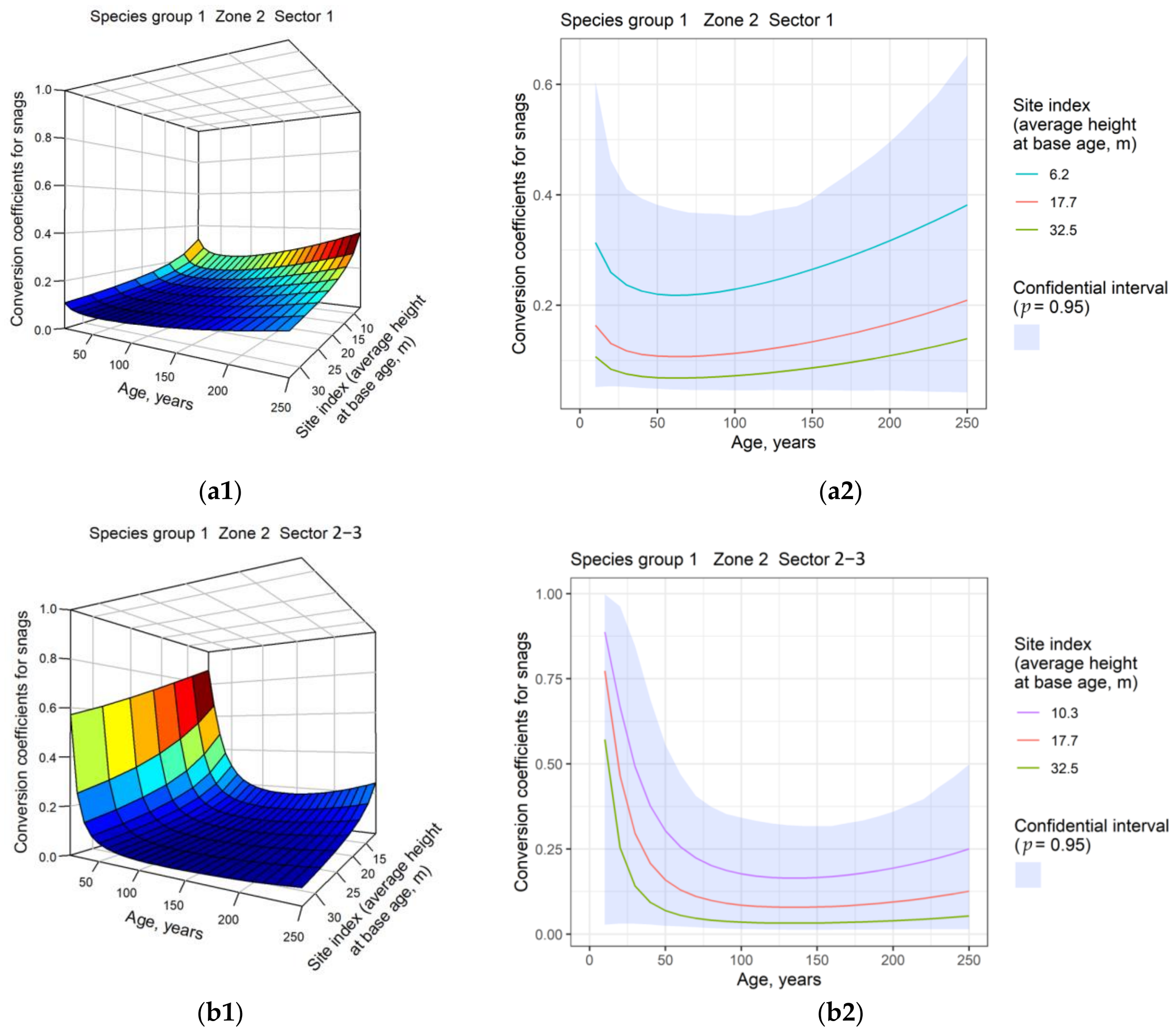
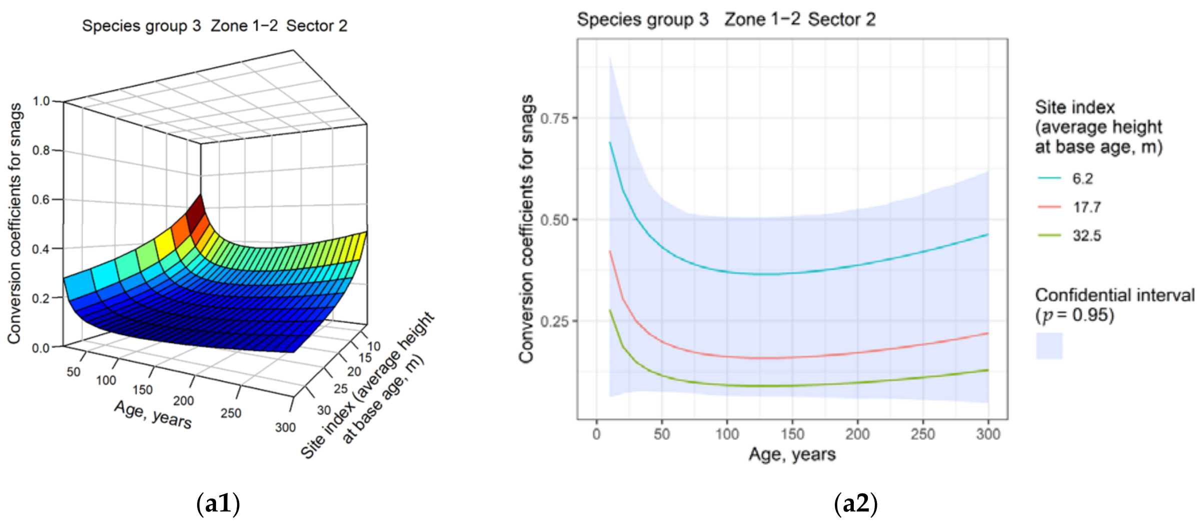


Figure 2. Dead wood expansion factors for Pine snags, bioclimatic zone 2 (middle taiga). (**a1**,**a2**)—region 1 (European part), (**b1**,**b2**)—combined regions 2 (Siberia) and 3 (Far East).



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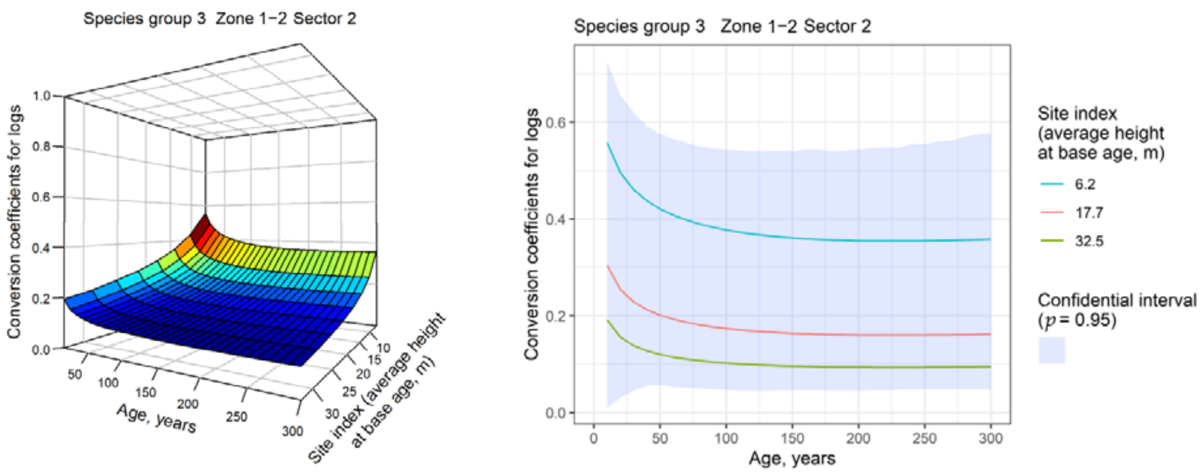
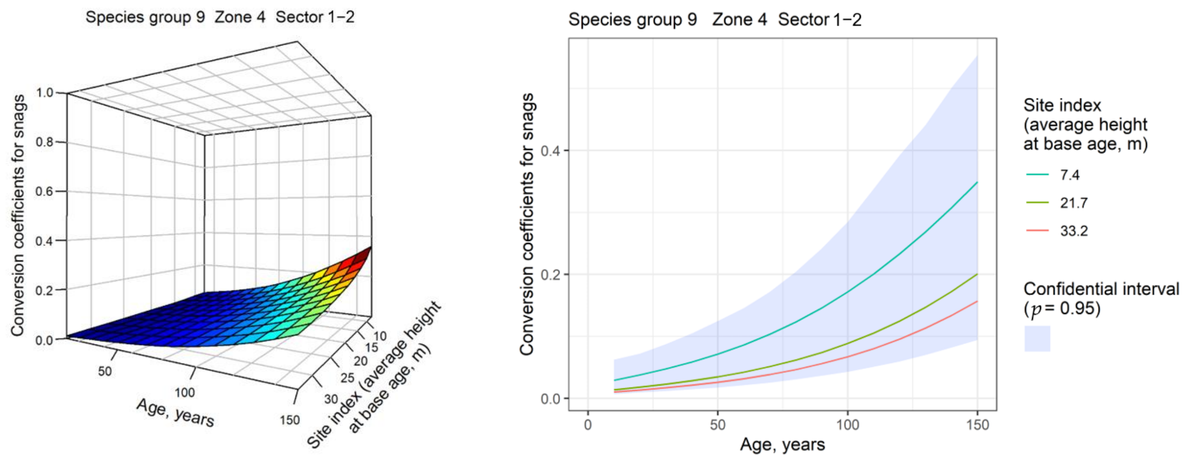
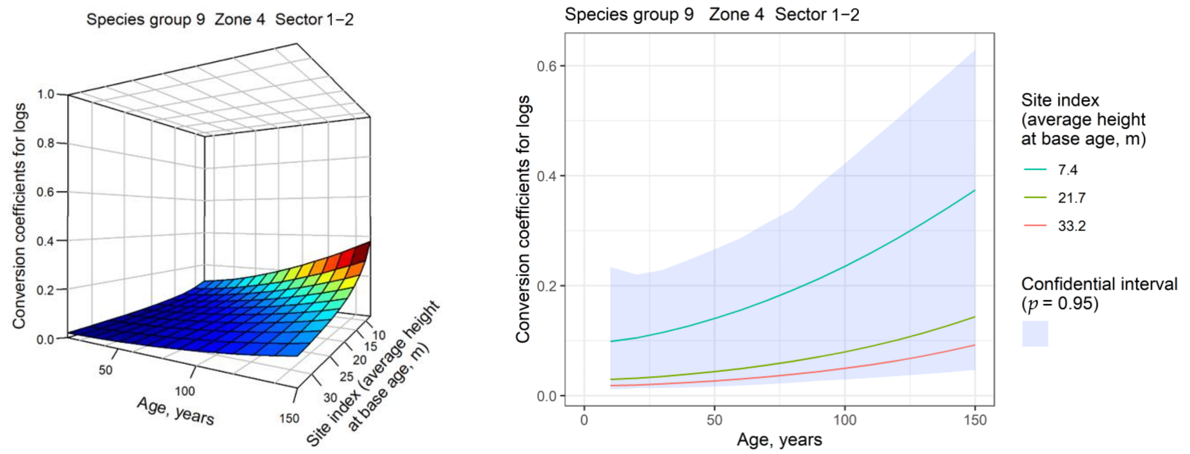


(**b1**) (**b2**)

Figure 3. Dead wood expansion factors for a group of species 3—dark coniferous included *Picea* spp. and *Abies* spp.), combined bioclimatic zones 1 and 2, as well northern and middle taiga). (**a1**,**a2**)—snags, region 1 (European part), (**b1**,**b2**)—logs, combined regions 2 (Siberia) and 3 (Far East).



(**a1**) (**a2**)



(**b1**) (**b2**)

Figure 4. Dead wood expansion factors for group of species 9—softwood birches, bioclimatic zone 4—combined zone of temperate forests, forest steppe and steppe. (**a1**,**a2**)—snags, (**b1**,**b2**)—logs, combined regions 1 (European part) and 2 (Siberia).

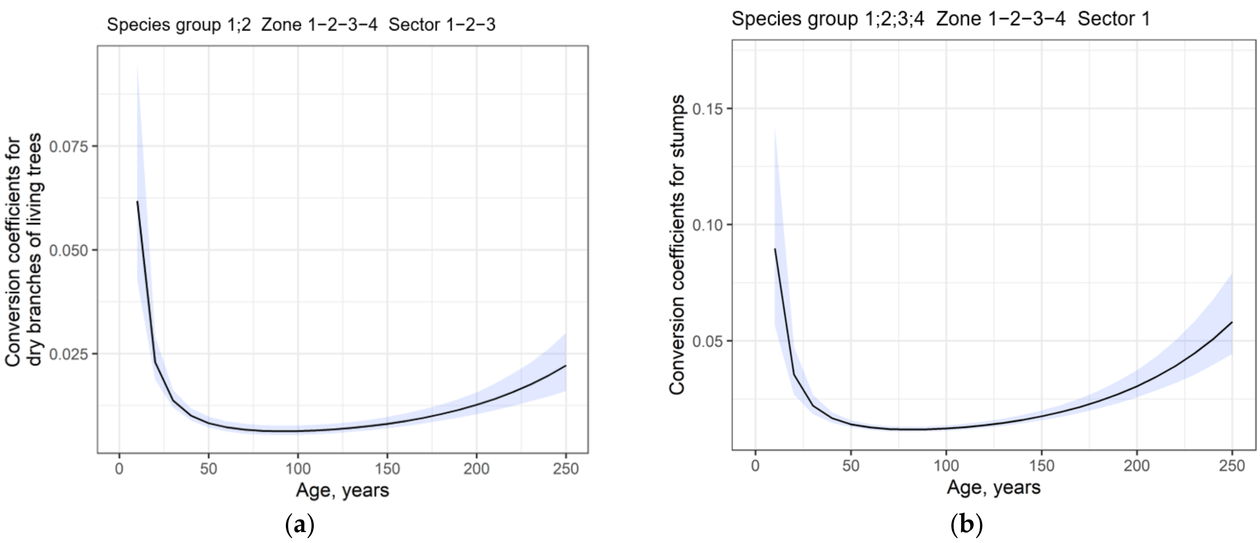


Figure 5. Dead wood expansion factors: (**a**) aboveground biomass of stumps of coniferous species (groups of species 1, 2, 3, 4) in the European part (region 1); (**b**) biomass of dry branches of living trees for pine and larch (groups of species 1 and 2) in the European part (region 1).

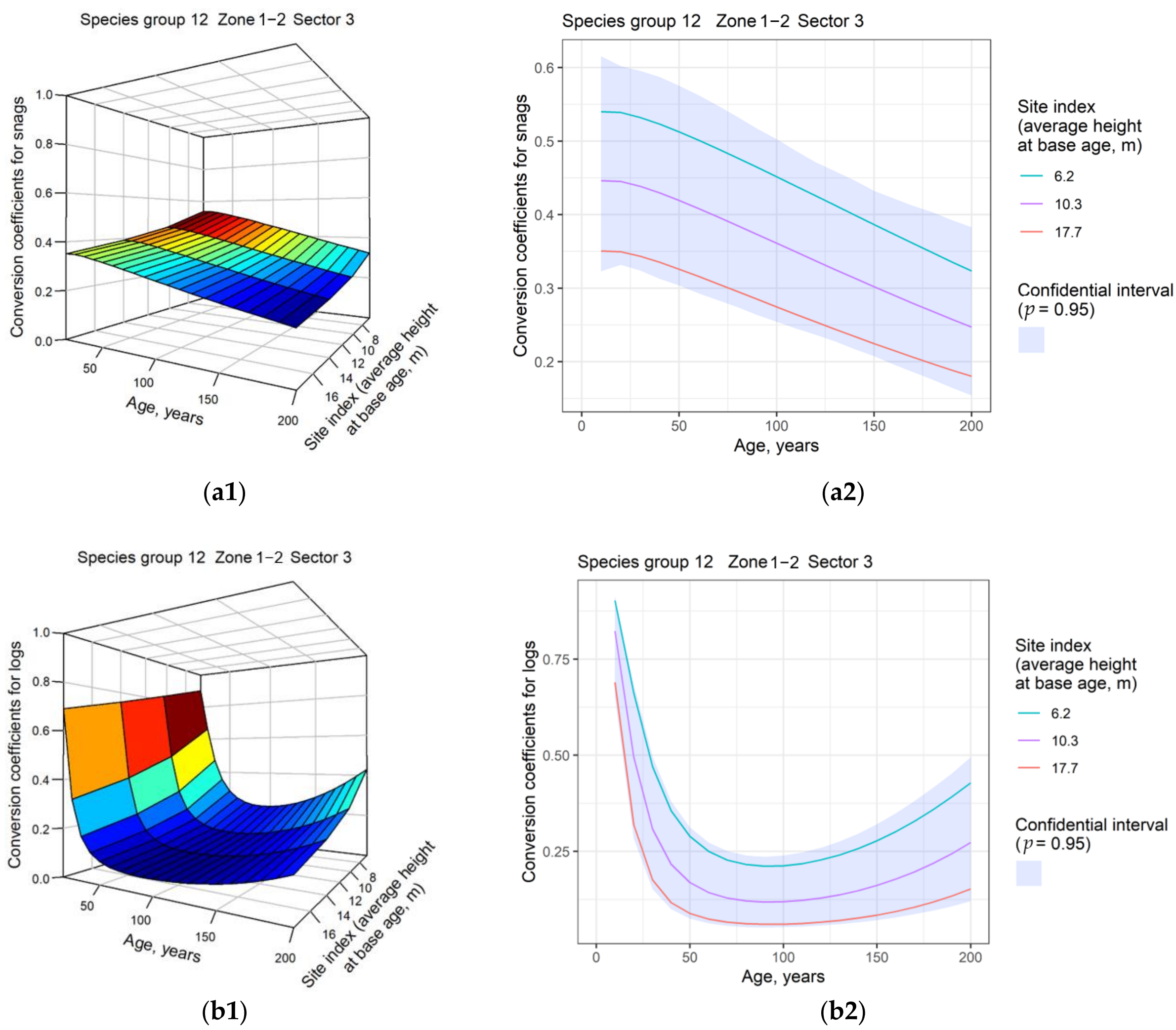


Figure 6. Dead wood expansion factors for group of species 12—dwarf pine (*Pinus pumila*), bioclimatic zones 2,3, regions 2 and 3; (**a1**,**a2**)—model parameters for snags, (**b1**,**b2**)—for logs.

3.2. Density of Dead Wood

Wood density depends on numerous factors that act in a complicated and interconnected manner, which include tree species, age, productivity level (site index), geographical and landscape conditions, peculiarities of stem wood decay, and the type and severity of previous disturbances, particularly, fire and insect outbreaks. Overall, at the continental scale, two common trends of spatial change in the dead wood density can be observed: a decrease from north to south for the same tree species, and—at the same geographical location—an increase from forest stands of higher to lower productivity.

These average common trends may be substantially modified by different regional impacts. Overall, the density of stem wood of all species across NE was reported to decrease by 0.25% by one degree latitude in the direction from south to north and by 0.26% for each degree longitude from west to east. The tendency for stem bark change is similar, with decreases of 0.55% and 0.28%, respectively [95].

At the same time, the variability in the density of intact, or undecayed wood of growing trees of the same species, may be surprisingly high, which impacts the density of decaying wood. For instance, the estimates of the density of the stem wood of pine (*Pinus sylvestris*) in the Asian part of NE varies from 0.38 to 0.53 Mg m^{-3} (the average from 16 studies is 0.476 ± 0.037 Mg m^{-3}), those of Siberian larch (*Larix sibirica*) from 0.53 to 0.73 Mg m^{-3} (average 0.641 ± 0.056 Mg m^{-3}, n = 11) and for Cajander larch (*L. cajanderi*) from 0.5 to 0.67 Mg m^{-3} (average 0.624 ± 0.048 Mg m^{-3}, n = 11). Within the relatively small territories of the Far-Eastern middle taiga to the north of the Amur River, the density of oven-dry stem wood varied from 0.404 to 0.453 for pine and from 0.487 to 0.616 Mg m^{-3} for Cajander larch [85,86].

Taking into account the high spatial diversity of dead wood density, it seems logical to recommend, at this stage for practical use, the average values of wood density by the latitudinal belts for the entire region of the study. Such an estimate has been done based on all available information including the database and the auxiliary information mentioned above (Table 1). In practical inventories of dead wood, it is recommended to include the estimate of logs in the estimate for stumps, and the result for dry branches of living trees in the estimate of snags.

Table 1. Mean density of snags and logs for the main forest forming tree species (kg m^{-3}) by aggregated longitudinal belts [1].

Tree Species	Density of Snags				Density of Logs			
	NT [1]	MT [1]	ST [1]	TF [1]	NT [1]	MT [1]	ST [1]	TF [1]
Pine	450	395	382	384	328	268	255	290
Larch	460	440	418	313	325	288	276	205
Spruce, Fir	430	398	362	350	380	291	216	264
Siberian pine	340	300	329	367	320	287	206	214
Oak			520	520			510	510
Stone birch [2]	505	480	457	445	400	395	380	360
Other HW [3]	510	490	470	455	450	425	395	380
Birch	505	398	365	453	431	196	177	280
Aspen	430	368	359	394	380	216	170	252
Siberian dwarf pine	560	500	440	420	380	365	305	325

[1] Zonal latitudinal belts: NT—forest tundra and northern taiga, MT—middle taiga, ST—southern taiga, TF—zone of temperate forest, forest steppe and steppe. [2] Including Far Eastern hardwood birches (*Betula ermani, B. costata* Trautv. Etc.). [3] Other hard wood deciduous species.

An interesting fact can be noted based on Table 1—for a substantial part of the dominant tree species (that is more noticeable for logs) of the southern (4st) zone, which has a relatively small forest cover and almost exclusively managed forests, density of wood increases opposite to the general trend of decreasing dead wood density from north to south. Probably, this can be explained by the increase of intensity of management and use of dead wood by the local population.

3.3. Carbon Fraction in Dry Matter of Dead Wood

Most estimates of the carbon fraction (CF) in the dry matter of dead wood protocols utilize a default dead wood CF of 50%. However, live tree studies suggest that this value is an over-estimate. The most comprehensive review of the CF in dead wood globally [96] reports average values of CF of 48.84 ± 0.76% with a range for 40.69%–56.98% for boreal forests and an average value of 49.29% ± 0.74% with a range of 41.29%–57.28% for temperate forests. The other aggregated results of this study were (%%): by position—downing wood 47.81 ± 1.05, standing 48.20 ± 1.06; by decay classes—47.53 (1st class), 47.55 (2nd), 47.98 (3rd), 48.68 (4th) and 48.67 (5th); and by components of dead wood—stem 48.02 ± 1.07, roots 47.79 ± 1.14, branches 45.67 ± 1.34; bark 48.73 ± 1.08 and fine tissue 48.89 ± 1.23%. The value for angiosperm species was 47.18 ± 0.79 and gymnosperm was 49.19 ± 0.79 [96]. Similar results have been reported in other publications, e.g., [97].

While coniferous tree species showed statistically significant higher weighted mean CF compared with deciduous tree species (53.0 ± 0.1% vs. 51.6 ± 0.1%), the variation in the weighted mean CF within the tree species exceeded the variation in the weighted mean C content between species [98]. However, the CF for some boreal deciduous species was substantially higher in some studies. For example, the CF for American mostly boreal birch (*B. papyrifera* Marshall) was reported to be 65.0 ± 3 [99] and 60.0 ± 1.4 [100], which probably differs depending upon the specifics of the landscapes.

Many years of research in Siberia (e.g., Mukhortova et al. [3,101,102]) has led to the following conclusions. For snags, the range of CF values is small, for instance, in forest tundra for spruce, 45.8%–46.9% (average 46.8 ± 0.2), larch, 45.8%–46.9% (average 46.2 ± 0.3); and fir in southern taiga, 48.4%–50.1% (average 49.0 ± 0.3). The values of the CF are independent of both the "age of the snags" and the stage of decay. For logs, a similar picture can be observed: there is no dependence on the stage of decay or there is a small increase to the 3rd class of decay. In the absolute majority mentioned above, the changes are statistically insignificant.

Taking into account such a variability and the fact that assessing the CF by different methods (e.g., the optical analytical system PSCO/ICI IBM-PC 4250) vs. results of measurement by CN analyzer gives a difference of 5%–10%; then, for the inventory of dead wood across all NE, the unified value of the CF of 48.0% can be recommended for the dead wood of all forests, or the aforementioned individual values for coniferous and deciduous species separately.

4. Discussion

Overall, the models developed here have satisfactory statistical indicators. An analysis of the residuals shows the absence of statistically significant biases in practically all of the regional models. The results obtained in this study confirm the fairly consistent general conclusions found in previous studies that the amount of CWD found across large geographical regions depends mainly on the tree species, the age, the intensity of the silvicultural treatment and the age of forest stands, and within these strata, on geographical location (bioclimatic zone) and the level of forest productivity [25,103,104].

For a major part of the NE territories, typically, for basically unmanaged taiga forests at high latitudes, the DWEF equations for most of the components, i.e., snags and logs, are presented in a U-shaped form, dependent on age (e.g., Figures 1, 2 and 5). The high values of DWEFs for young forests can be explained by two main reasons: the low GSV of stands at the initial stages of post disturbance successions and by a substantial amount of CWD remaining after the previous stand replacing disturbances.

The patterns of the temporal dynamics of DWEF depend substantially on the extent, frequency and severity of the disturbances. This factor is the most influential in the Asian part of the study region. The damage caused by disturbances there have markedly increased in the last few decades. During the period 2017–2021, forest fire enveloped around 15 to 20 million ha annually, and the mortality of forests in burnt territories (i.e., the share of stand replacing fires) was high—around 50% of the area was enveloped by fire [50]. The annual area of insect outbreaks in some years exceeded 5 million ha. The amount of harvested wood has substantially increased during the last two decades [105]. According to remote sensing estimates, Russia has lost around 10 million ha of tree cover in the last decade from 2010–2019 [50].

The replacement of coniferous forests by pioneer deciduous species (birch, aspen) is a typical process after stand-replacing disturbances in the NE taiga forests. This explains the distribution of such succession development patterns in young deciduous forests. Overall, this results in the increase of areas with a U-shape accumulation of CWD occurring there.

Comparatively, there is a substantial difference in the temporal dynamics of CWD if a forest is harvested or killed by a disturbance and then is artificially regenerated afterwards. A major part of the post disturbance amount of dead wood is removed during site preparation, planting and subsequent silvicultural treatments. Overall, the share of intensively managed forests increases towards the south in the European part of NE and becomes predominant in zone 4, where CWD accumulation follows the J-shape form of dead wood dynamics with age. In general, the share of intensively managed forests is rather small due to the low level of artificial regeneration in the Asian part of NE. The share of planted forests after stand-replacing disturbances and clear cuts calculated here constitutes ca. 200 thousand ha per year, i.e., about 10% of the total area of stand replacing disturbances over this region during the last decade.

The aforementioned factors may lead to substantial uncertainties in the estimates of the amount of CWD of forests in individual stands. Separating the models by regions and bioclimatic zones reflects typical management practices in the regions and decreases the probability of potential biases in the estimates but does not exclude them completely.

One of the main goals of the models developed here is to minimize potential errors for relatively large forest territories. The "regionalization" provided here is one of the substantial tools for achieving this. A typical example is presented in Figure 7. Even for forests with the same productivity, the dynamics of the share of snags in the Northern taiga is higher compared to that in a temperate forest zone (Figure 7), especially for young and old forests. Such a dependence reflects both the change in growth conditions and the level of forest management. The latter follows from the absence of or negligible levels of dead wood management in the major northern part of NE and the higher decomposition rate of dead wood in the south.

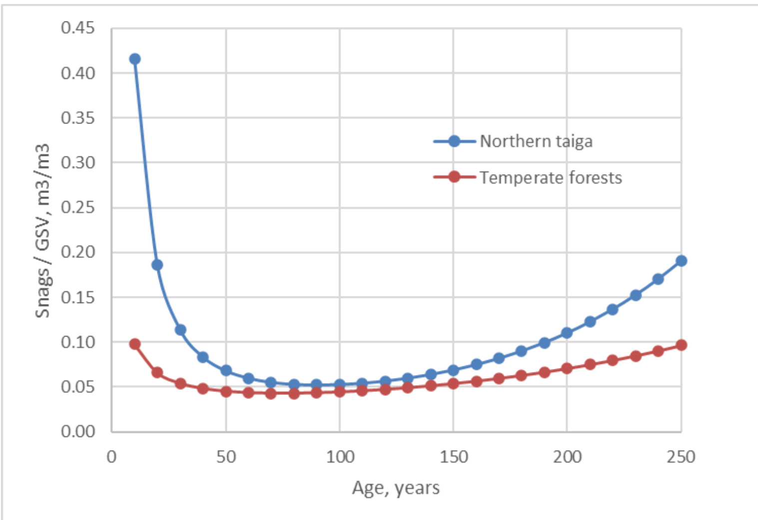


Figure 7. Comparison of Pine snag DWEF dynamics model behavior for the European northern taiga and temperate forests (SI = 21.4 m).

A reliable comparison of the models developed here with previous estimates of the amount of dead wood in Russian forests could only be undertaken approximately for a number of reasons: (1) the scientific assessment of the amount of dead wood is not accessible for all countries of the study region; (2) there is no assessment among previous ones that considers all 4 components of dead wood in forests; (3) the use of different definitions of some components of dead wood; (4) and the use of corrections in the system developed here would account for the intensity of the disturbance regimes (mostly wildfires) in the year of the account [106]. However, we provide some comparisons for Russia, which comprises more than 90% of NE forests.

4.1. Application of Models for the Vologda Region

We applied our equations to the NFI data for the Vologda region of the Russian Federation, situated in the middle and southern taiga of the European part of Russia. According to the NFI, the Vologda region has 10.3 Mha of forest with 2.4 bill. m^3 of GSV. Spruce and pine consist of 45% of the GSV, while the rest of the GSV is represented by deciduous species (mostly aspen and birch). The age of the forest stands ranged from 6 to 200 years old, and the average age was 65 years. A comparison of the model results with NFI-based estimates for 2014 (year with the average fire danger) is presented in Table 2.

Table 2. Comparison of the model and NFI-based estimates of CWD in the Vologda region.

CWD Fraction	Our Estimation, m^3 ha^{-1}	NFI-Based Inventory, m^3 ha^{-1}	Difference, %
Snags	15.5	13.6	14
Logs	25.5	20.9	22
Stumps	3.2	1.9	68
Dry branches of living trees	2.8	NA	
Total CWD	47.0	36.3	29

Our CWD estimation is 29% higher compared to the NFI of the region, or 21% higher if dry branches are excluded from the account. The difference can be explained by the definitions. We considered CWD starting from 1 cm in diameter. The NFI accounted for snags and logs from 6 cm in diameter, with the length of logs of at least 50 cm according to the NFI manual. Stumps were included starting from 14 cm in diameter. The best match in the definitions is for snags, which leads to the smallest difference in the estimations (i.e., 14%). The most serious mismatch in definitions is for the stumps, which leads to the largest disagreement (i.e., 68%). The major reason for such a discrepancy is probably the fact that this region is the one with the most intensive amount of harvesting. Other reasons may contribute to this difference, e.g., such potential errors may arise from the small areas of the sample plots, etc. The CWD structure (snags/logs/ stumps) is similar in both the model (35/58/7%) and the NFI (37/58/5%).

The stock of the stumps and dry branches of living trees comprises a relatively small part of the total amount of the CWD of the forests of NE. The preliminary estimates from the models developed here for Russian forests (as of around 2015, the area of 760 M ha) resulted in around 3.0% for stumps and 4.0% for dry branches. Taking into account a very approximate knowledge of these components of CWD, it seems relevant to join stumps with logs and dry branches with snags in the further consideration of the role of CWD in the carbon budget of forest ecosystems.

According to the results of the first cycle of the NFI, the total volume of dead wood in Russian forests makes up around 23.76 billion m^3. A preliminary estimate from the application of the models developed here is 29.18 billion m^3 for around 2015, i.e., +23%, which is close to the above estimate for the Vologda region.

4.2. Uncertainties and Cautionary Notes

The phenomenon studied here has a number of specific features that define it as an underspecified (fuzzy) system such as: some of the indicators used are the result of qualitative expert estimates; the definitions of some important indicators are not completely harmonized across different fields of knowledge and these differences need to be acknowledged; the experimental indicators collected here do not represent the results of the full planned experiment and a substantial part of the territories studied here are very poorly represented by the data; the sample plots were established over a long time under conditions of a changing environment; among others. For such systems, estimates of the uncertainties are inevitably incomplete because they do not allow us to assess the structural uncertainties (Shvidenko et al., 2010) and include expert conclusions and professional judgements.

However, the expert analysis shows that all the above uncertainties, which are inevitable for large scale assessments of major forest indicators under climate change, do not contain biases that would hinder the practical use of the final results. Based on expert judgements, we can conclude that for a relatively large forest territory, the total error (i.e., the sum of the systematic and standard errors) does not go outside of the 10% range around the estimates, considering a rather high confidence interval (e.g., around 0.9).

It is also necessary to take into account the fact that the database developed here is in essence static because it does not contain any mechanism for accounting for the impacts of climate change on forests. This problem has two components. First, the direct impact of a changing climate on the growth and vitality of forests (e.g., dryness of forests due to water stress) should be taken into account, and the explosive increase in the occurrence of natural disturbances, primarily wildfire and outbreaks of dangerous insects, which are even more dangerous when considering forest ecosystems.

The problem is that extreme weather and the consequent disturbances are currently localized within large regions yet are accompanied by a substantial change in the amount of dead wood. The models developed here do not take any changes in the disturbance regimes into account. As an immediate temporary solution, the system of corrections, connected to the changing severity in disturbance regimes, could be used to improve the predictions for strongly affected regions. Nevertheless, further development in the systems of forest monitoring remains one of the basic pillars in the transition to sustainable forest management, where forests are resilient to the accelerated impact of disturbances. A system of models similar to those developed in this paper could be introduced into modern monitoring systems to transform them into quasi-dynamic systems that would take the main consequences of the alteration in disturbance regimes into account and directly connect the impacts of climate change on forest stands to allow for the implementation of appropriate management operations.

5. Conclusions

This study presents an attempt to apply, as consistently as possible, some of the important principles of applied systems analysis and statistical modelling in the development of a system for assessing the amount of dead wood in the forests of NE. The initial database contains around 3800 sample plots of different types and represents the most complete organized collection of information on dead wood in NE. The system can be applied in different ways: (1) in its current form for average regimes of intensity of natural and human induced disturbances; (2) with regional corrections on changing disturbance regimes; and (3) within a system of forest monitoring. The latter approach allows for the static character of the system under consideration to be changed into a dynamic one, applicable for monitoring systems that will be applied to the operational recognition of changes in forest resilience in a rapidly changing world. Further studies are needed to further quantify the effect of disturbances and climate change on the dead wood pool and on its dynamics.

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Appendix A

Table A1. Average stand height (m) for different Site Indexes in the base age [83] Equation (1).

Site Index by M.M. Orlov	Birch, Aspen and Other Deciduous Softwood Species (50 Years Old)	Siberian Pine (160 Years Old)	Other Species (100 Years Old)
If	36.1	58.4	51.1
Ie	33.2	54.1	47.4
Id	30.4	49.9	43.7
Ic	27.5	45.7	40.0
Ib	24.6	41.4	36.3
Ia	21.7	37.2	32.5
I	18.9	33.0	28.8
II	16.0	28.7	25.1
III	13.1	24.5	21.4
IV	10.3	20.2	17.7
V	7.4	16.0	14.0
Va	4.5	11.7	10.3
Vb	1.6	7.5	6.2

Table A2. Parameters of Equation (2) for the snags.

Species	Zonal Belt [1]	Region	Equation (2) Parameter Estimate				SI Min	SI Max	N
			$\hat{a}_0$	$\hat{a}_1$	$\hat{a}_2$	$\hat{a}_3$			
Pine	NT	Eur	6.8200	−1.9474	−0.9431	0.0215	6.2	25.1	145
		Sib, FE	8.5502	−1.9988	−1.0136	0.0131	6.2	25.1	34
	MT	Eur	1.7497	−0.4954	−0.8071	0.0079	6.2	32.5	115
		Sib, FE	10.5683	−2.2041	−1.5417	0.0164	10.3	32.5	64
	ST	Eur	5.2691	−1.7731	−0.9136	0.0269	6.2	36.3	354
		Sib, FE	5.2236	−1.2030	−1.2495	0.0084	6.2	36.3	49
	TF	all	1.0621	−0.7655	−0.5297	0.0102	10.3	36.3	121
Larch	NT	Eur, Sib	6.8765	−1.7264	−0.6872	0.0125	6.2	25.1	63
		FE	4.9720	−0.9470	−1.4341	0.0089	6.2	25.1	63
	MT	Eur, Sib	9.1048	−2.1444	−1.1829	0.0132	6.2	32.5	21
		FE	7.2334	−1.7823	−0.8916	0.0133	6.2	32.5	176
	ST, TF	all	5.6436	−0.7945	−1.5649	0.0069	10.3	32.5	67

Table A2. *Cont.*

Species	Zonal Belt [1]	Region	Equation (2) Parameter Estimate $\hat{a}_0$	$\hat{a}_1$	$\hat{a}_2$	$\hat{a}_3$	SI Min	SI Max	N
Spruce & Fir	NT	Eur	5.0537	−1.2687	−0.7783	0.0057	6.2	32.5	119
	NT, MT	Sib	4.6096	−0.8350	−1.0655	0.0065	6.2	32.5	44
		FE	6.2442	−1.2784	−0.9923	0.0044	6.2	32.5	211
	MT	Eur	5.0894	−1.0595	−1.0815	0.0085	6.2	32.5	78
	ST	Eur	5.6316	−1.5316	−1.1929	0.0210	6.2	32.5	385
	TF	Eur	13.1209	−2.5432	−2.2282	0.0282	10.3	32.5	72
	ST, TF	Sib	7.9305	−2.1192	−0.9877	0.0208	10.3	32.5	45
		FE	3.4950	−0.8384	−0.7183	0.0125	10.3	32.5	102
Siberian pine	NT, MT	Eur, Sib	7.5877	−1.4001	−1.7818	0.0111	6.2	28.8	81
	ST, TF	Eur, Sib	7.1469	−1.3234	−1.3124	0.0091	10.3	28.8	30
	all	FE	5.8189	−1.0443	−1.1438	0.0057	10.3	28.8	43
Oak (seeding)	all	Eur, Sib	1.5762	−0.5070	−1.0163	0.0065	10.3	32.5	95
		FE	4.5711	−0.6933	−1.7409	0.0104	10.3	32.5	13
Oak (vegetative)	all	Eur, Sib	0.0377	0.7156	−1.3102	−0.0132	17.7	25.1	25
		FE	−1.2133	−0.1819	0	0.0048	–	–	20
Stone birch	NT, MT	any	7.3329	−1.714	−1.2438	0.0207	10.3	28.8	58
	ST, TF	any	5.5333	−1.2385	−1.1819	0.0123	10.3	28.8	51
Other hard wood deciduous	all	Eur	5.9115	−1.4696	−1.0995	0.0123	10.3	36.3	40
		Sib, FE	2.8698	−0.7634	−0.8186	0.0058	10.3	36.3	52
Birch	NT	all	0.5139	−0.2696	−0.6009	0.0087	1.6	21.7	43
	MT, ST	Eur, Sib	3.211	−1.2203	−0.9869	0.0243	1.6	33.2	271
		FE	5.4091	−2.0532	−0.8771	0.0392	4.5	24.6	28
	TF	Eur, Sib	−2.5939	0.1389	−0.7039	0.0179	7.4	33.2	175
		FE	3.1055	−0.8225	−1.1926	0.0216	7.4	33.2	24
Aspen	NT, MT	Eur, Sib	3.1628	−1.0131	−0.6457	0.0125	7.4	21.7	19
	ST, TF	Eur, Sib	−0.9267	−0.0264	−0.6672	0.0115	7.4	33.2	165
	any	FE	2.7013	−0.8677	−0.6018	0.0135	7.4	33.2	28
Other soft wood deciduous	all	all	1.1922	−0.2292	−1.0421	0.0104	10.3	47.4	199
Dwarf pine	all	all	1.3865	0.0804	−0.7405	−0.0060	6.2	17.7	17

[1] Zonal belts: NT—forest tundra and northern taiga, MT—middle taiga, ST—southern taiga, TF –zone of temperate forest, forest steppe and steppe; Regions: Eur—Europe, Sib—Siberia, FE—Far East.

Table A3. Parameters of Equation (2) for the logs.

Species	Zonal Belt [1]	Region	Equation (2) Parameter Estimation $\hat{a}_0$	$\hat{a}_1$	$\hat{a}_2$	$\hat{a}_3$	SI Min	SI Max	N
Pine	NT	Eur	3.1943	−1.0115	−0.8126	0.0111	6.2	25.1	95
		Sib, FE	3.8781	−1.1595	−0.5998	0.0137	6.2	25.1	20
	MT	Eur	1.1975	−0.3879	−0.8618	0.0098	6.2	32.5	76
		Sib, FE	4.4085	−0.9464	−1.3096	0.0131	10.3	32.5	31
	ST	Eur	0.4059	−0.2890	−0.7351	0.0087	6.2	36.3	295
		Sib, FE	5.0025	−1.8260	−1.0151	0.0336	6.2	36.3	22
	TF	all	3.0180	−0.6703	−1.4378	0.0154	10.3	36.3	42
Larch	NT	Eur, Sib	5.7553	−1.6704	−0.6508	0.0144	6.2	25.1	45
		FE	2.9246	−0.9414	−0.9269	0.0137	6.2	25.1	64
	MT	Eur, Sib	3.7574	−1.2037	−0.7747	0.0153	6.2	32.5	19
		FE	3.0147	−1.0510	−0.6187	0.0119	6.2	32.5	143
	ST, TF	all	5.7840	−1.4237	−1.3383	0.0216	10.3	32.5	59
Spruce & Fir	NT	Eur	1.6432	−0.5100	−0.6475	0.0087	6.2	32.5	110
	NT, MT	Sib	2.9403	−0.3844	−1.0089	0.0017	6.2	32.5	22
		FE	5.7795	−0.7887	−1.5619	0.0047	6.2	32.5	175
	MT	Eur	1.0327	−0.4380	−0.3854	0.0065	6.2	32.5	82
	ST	Eur	6.8443	−1.7546	−0.8392	0.0203	6.2	32.5	342
	TF	Eur	6.4503	−1.7393	−0.5777	0.0180	10.3	32.5	35

Table A3. *Cont.*

Species	Zonal Belt [1]	Region	Equation (2) Parameter Estimation				SI Min	SI Max	N
			$\hat{a}_0$	$\hat{a}_1$	$\hat{a}_2$	$\hat{a}_3$			
Siberian pine	ST, TF	Sib	4.1708	−1.0927	−0.8825	0.0120	10.3	32.5	20
		FE	2.0008	−0.4226	−0.8162	0.0060	10.3	32.5	53
	NT, MT	Eur, Sib	6.7510	−1.0259	−1.4742	0.0058	6.2	28.8	43
	ST, TF	Eur, Sib	8.6851	−1.8469	−1.2955	0.0150	10.3	28.8	28
	all	FE	6.1468	−0.8738	−1.4877	0.0063	10.3	28.8	24
Oak (seeding)	all	Eur, Sib	3.7627	−0.7628	−1.5642	0.0114	10.3	32.5	77
		FE	6.6664	−1.3906	−1.5361	0.0190	10.3	32.5	17
Oak (vegetative)	all	Eur, Sib	0.5087	0.3806	−1.1504	−0.0010	17.7	25.1	25
		FE	−1.677	0.1711	0	−0.0005	–	–	20
Birch ermanii	NT, MT	any	4.7927	−1.1345	−0.9600	0.0105	10.3	28.8	57
	ST, TF	any	4.6780	−1.2563	−0.6701	0.0126	10.3	28.8	62
Other hard wood deciduous	all	Eur	5.1406	−1.0669	−1.3779	0.0092	10.3	36.3	57
		Sib, FE	6.0375	−1.2662	−1.3725	0.0142	10.3	36.3	59
Birch	NT	all	1.6841	−0.8087	−0.6230	0.0160	1.6	21.7	61
	MT, ST	Eur, Sib	2.0303	−0.9369	−0.4805	0.0110	1.6	33.2	265
		FE	2.3569	−0.9765	−0.5167	0.0107	4.5	24.6	33
	TF	Eur, Sib	0.2452	−0.1023	−1.1800	0.0141	7.4	33.2	91
		FE	1.8109	−0.6131	−0.8452	0.0140	7.4	33.2	25
Aspen	NT, MT	Eur, Sib	7.5838	−2.1400	−1.0838	0.0306	7.4	24.6	27
	ST, TF	Eur, Sib	−0.4077	−0.1946	−0.7325	0.0163	7.4	33.2	196
	all	FE	0.0059	−0.4884	−0.4553	0.0185	7.4	36.1	39
Other soft wood deciduous	all	all	1.3246	−0.5520	0	−0.7672	10.3	47.4	226
Dwarf pine	all	all	10.5273	−2.6527	−1.3596	0.0286	6.2	17.7	19

[1] Zonal belts: NT—northern taiga, MT—middle taiga, ST—southern taiga, TF—temperate forest; Regions: Eur—Europe, Sib—Siberia, FE—Far East.

Table A4. Parameters of Equation (2) for stumps.

Species	Zonal Belt [1]	Region	Equation (2) Parameter Estimation				SI Min	SI Max	N
			$\hat{a}_0$	$\hat{a}_1$	$\hat{a}_2$	$\hat{a}_3$			
Coniferous	all	Eur	1.4474	−1.7263	0	0.0212	–	–	1006
	all	Sib, FE	3.3154	−1.9787	0	0.0172	–	–	300
Hard wood deciduous	all	all	−0.8251	−0.9562	0	0.0106	–	–	125
Soft wood deciduous	all	all	1.4504	−1.9928	0	0.0352	–	–	546

[1] Zonal belts: NT—northern taiga, MT—middle taiga, ST—southern taiga, TF—temperate forest; Regions: Eur—Europe, Sib—Siberia, FE—Far East.

Table A5. Parameters of Equation (2) for the dead branches of living trees.

Species	Zonal Belt [1]	Region	Equation (2) Parameter Estimation				SI Min	SI Max	N
			$\hat{a}_0$	$\hat{a}_1$	$\hat{a}_2$	$\hat{a}_3$			
Pine and larch	all	all	1.146	−1.7627	0	0.0192	–	–	270
Dark coniferous	all	all	−0.7096	−0.9952	0	0.0133	–	–	125
Hard wood deciduous	all	all	−1.3453	−0.9776	0	0.0176	–	–	22
Soft wood deciduous	all	all	−1.4545	−1.1717	0	0.0249	–	–	62

[1] Zonal belts: NT—northern taiga, MT—middle taiga, ST—southern taiga, TF—temperate forest; Regions: Eur—Europe, Sib—Siberia, FE—Far East.

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