

Article

# Improved Estimates of Biomass Expansion Factors for Russian Forests

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**Abstract:** Biomass structure is an important feature of terrestrial vegetation. The parameters of forest biomass structure are important for forest monitoring, biomass modelling and the optimal utilization and management of forests. In this paper, we used the most comprehensive database of sample plots available to build a set of multi-dimensional regression models that describe the proportion of different live biomass fractions (i.e., the stem, branches, foliage, roots) of forest stands as a function of average stand age, density (relative stocking) and site quality for forests of the major tree species of northern Eurasia. Bootstrapping was used to determine the accuracy of the estimates and also provides the associated uncertainties in these estimates. The species-specific mean percentage errors were then calculated between the sample plot data and the model estimates, resulting in overall relative errors in the regression model of  $-0.6\%$ ,  $-1.0\%$  and  $11.6\%$  for biomass conversion and expansion factor (BCEF), biomass expansion factor (BEF), and root-to-shoot ratio respectively. The equations were then applied to data obtained from the Russian State Forest Register (SFR) and a map of forest cover to produce spatially distributed estimators of biomass conversion and expansion factors and root-to-shoot ratios for Russian forests. The equations and the resulting maps can be used to convert growing stock volume to the components of both above-ground and below-ground live biomass. The new live biomass conversion factors can be used in different applications, in particular to substitute those that are currently used by Russia in national reporting to the UNFCCC (United Nations Framework Convention on Climate Change) and the FAO FRA (Food and Agriculture Organization's Forest Resource Assessment), among others.

**Keywords:** BEF; BCEF; root-to-shoot ratio; forest biomass structure; Northern Eurasian forests

## 1. Introduction

Forest biomass is an important input to the monitoring and implementation of the United Nations Sustainable Development Goals [1], providing humans with materials and renewable energy, securing carbon stocks, providing links to biodiversity and recreation, and supporting agricultural production. Biomass structure is represented by biomass expansion factors and the root-to-shoot ratio ( $R:S$ ), which are important characteristics that are used to estimate biomass components based on growing stock volumes ( $GSV$ ), and to quantify the inter-tree allocation of biomass. The biomass structure of forest ecosystems includes live biomass, which is divided into the live biomass of trees (stands) and the lower layers such as the understory, undergrowth and green forest floor; and dead vegetation matter including standing dry trees (snags), fallen wood (logs), stumps, dead roots and dry branches of live trees. In many cases, the assessment is limited to only the aboveground live biomass of trees, e.g., in applications of remote sensing [2]. In this paper, we consider live biomass of trees both above- and belowground.

Biomass structure and its indicators are different for different tree species depending on climate and soil conditions, and they vary substantially by forest type, age, levels of productivity, and stand stocking [3–5]. Direct measurement of biomass structure is labor intensive and limited to either destructive sampling or the more recently introduced terrestrial LiDAR scanning (with some limitations). However, the limited amount of relevant measurements may lead to substantial biases in the estimates of biomass structure. For example, substantial underestimation of root biomass by Earth system models has been reported previously by Song et al. [6].

Above-ground biomass of individual trees or stands is typically assessed by allometric equations [7,8]. However, existing models do not consider all of the significant factors that control the forest biomass structure. For instance, Forrester et al. [9], who provide an overview of existing European biomass models through nearly 1000 models collected in a database, claim that age and stand density are rarely used in the models, yet they are important drivers of biomass structure. The most popular independent variables were tree size, in terms of diameter or height, the number of trees per hectare, the basal area, and climatic parameters (mean annual temperature and mean annual precipitation) [9]. At the same time, the selection of independent variables in the regression equations depends upon available information. Thus, existing well-elaborated allometric equations [10] cannot be used for large scale assessments because they are based on variables (i.e., individual tree diameter and height distribution) that are not available in the aggregated data of forest inventories undertaken at regional and national scales (e.g., the Russian State Forest Register—SFR [11]).

One of the most important and practical applications of the knowledge of live biomass structure is its assessment for national reporting to the Secretariat of the Intergovernmental Panel on Climate Change (IPCC). The guidance from the IPCC considers the following fractions ( $M_{fr}$ ) of forest tree biomass: stem wood over bark ( $M_{st}$ ), branches ( $M_{br}$ ), foliage ( $M_{fol}$ ) and roots ( $M_{ro}$ ). “Stem wood over bark” refers to stem wood with bark. Stumps are included in the roots pool, while the tree tops are allocated to the branches. The biomass expansion factor ( $BEF$ ) is defined as the ratio of aboveground oven-dry biomass ( $AGB$ ) to either the commercial or stem oven-dry biomass including bark [12] (Equation (1)):

$$BEF = \frac{AGB}{M_{st}} = \frac{M_{st} + M_{br} + M_{fol}}{M_{st}}, \quad (1)$$

The Biomass Conversion and Expansion Factor ( $BCEF$ ) combine the conversion and expansion processes and help to convert the  $GSV$  into  $AGB$  [13] (Equation (2)) directly:

$$BCEF = BEF \cdot D = \frac{M_{st} + M_{br} + M_{fol}}{GSV}, \quad (2)$$

where  $D$  is basic wood density (or specific gravity), in tons of oven-dry matter per  $m^3$  stem volume;  $M_{st}$ ,  $M_{br}$ ,  $M_{fol}$  are the live biomass of stems, branches, and foliage, respectively, oven-dry  $t\ ha^{-1}$ ; and  $GSV$

is the growing stock volume in  $\text{m}^3$ . The *BCEF* has the dimension ( $\text{t m}^{-3}$ ) and can be applied directly to volume-based forest inventory data or remotely sensed estimates without needing information about basic wood densities (and the associated uncertainties). To define belowground live biomass, the IPCC recommends using the root-to-shoot ratio (*R:S*), i.e., the ratio of the belowground tree live biomass to the aboveground one.

Due to the large extent of Russian forests (more than one-fifth of the global forest area, [14]), the development of reliable sets of *BEFs* and *BCEFs* for Russian forests is interesting from both national and international points of view. There have been noticeable improvements in the models for assessing live biomass and its structure as applied to Russian forests over the last two decades as well as improvements to the amount and distribution of experimental data.

The first set of *BEFs* for the tree parts of forest ecosystems was published by Alexeyev and Birdsey in 1998 [15]. The amount and geographical distribution of sample plots were not reported at that time. All *BEFs* were obtained by graphical fitting of major forest forming species and large geographical regions of Russia. Any numerical conclusions about uncertainties were not reported. Nevertheless, it was the first attempt to present *BEFs* for assessing the biomass of forest ecosystems over the entire country.

Another team (Zamolodchikov et al.) published a set of *BCEFs* in 2003 [16] using a database containing ~2000 sample plots. The sample plots were aggregated (averaged) by 10 dominant species (and two aggregations of softwood and hardwood deciduous tree species) and age groups within three latitudinal belts over the country. The coefficients were applied to data from the SFR and were calculated as mean values by geographic units with corresponding standard errors. In addition to the very large and heterogeneous areas of the latitudinal belts, the study did not consider how much the missing input information (i.e., productivity and stocking) impacted upon the accuracy of the *BCEFs*.

Usoltsev [17–20] used a constantly growing database of forest biomass measurements to produce a regionalized system of *BCEF* equations as a function of forest age, average height, average diameter (DBH) and number of trees (*N*). Equations by Usoltsev can be directly applied to yield tables or individual forest stands where DBH and *N* are known. However, DBH and *N* are not contained in the SFR. In order to utilise the SFR data, Usoltsev also provided regional and tree specific regression equations where the *BCEF* depends on age and *GSV* [20]. However, this approach does not consider that the same *GSV* can have two types of stands: low productive but dense and high productive but sparse, which is critical to the biomass structure. For example, low productive forests invest more in below-ground biomass; sparse forests shift the biomass share from stems to branches (e.g., [21]).

At the same time, a team at the International Institute for Applied Systems Analysis (IIASA) applied a systems approach to the assessment of *BCEFs* for Russian forests for use of SFR data [5] aimed at (1) using all available experimental data collected at that time (about 3500 sample plots), (2) following strict statistical procedures, and (3) decreasing the level of uncertainty by accounting for the specifics of Russian forests and the corresponding forest inventory data. The *BCEF* in this study is based on a non-linear dependence of  $BCEF_{fr}$  on indicators available from aggregated data of the SFR: tree species, age, site index and relative stocking. This is the most comprehensive set of parameters that controls forest biomass structure, which are available in the SFR.

More than 10 years have now passed since this publication [5]. The amount of experimental data available, their spatial distribution and the quality have increased substantially, and new statistical methods have been applied during this period. These advances have therefore driven this research and defined the major objective of this study, i.e., to develop a new, more reliable system for estimating *BCEFs* and to compare them with those currently used for international reporting by Russia to international bodies such as the IPCC and the Food and Agriculture Organization's (FAO) Forest Resource Assessment (FRA).

## 2. Materials and Methods

The methodology consists of two principal steps: (1) estimation of the regression models of forest biomass structure based on field measurements, and (2) development of a map of the spatial distribution of biomass structure indicators using inventory-based biometric characteristics of forest cover.

### 2.1. Experimental Data

The experimental data used in this assessment consisted of 8007 unique records of sample plots based on destructive biomass sampling. The sample plots were established in the territories of Northern Eurasia and collected in a verified forest biomass database [21]. The database contained several key indicators of forests (geographical coordinates, dominant tree species, average age, site index, relative stocking, growing stock volume), the mass of live biomass fractions of trees (including stem wood over bark, wood of branches over bark, foliage and roots) and lower forest layers (understory, undergrowth and green forest floor). The data were collected from ca 1200 experiments for the period 1930–2014. Some biomass fractions were sampled more intensively (6315 records for stems, 6441—for branches, 6739—for foliage), while others much less (e.g., 3368—for roots). The accuracy of biomass estimation at the plot level is in the range of 92–94% for stem biomass, 80–90% for the crown and 70–80% for belowground biomass [21].

### 2.2. Forest Biomass Models

The forest biomass measurements from the sample plots [21] were used to fit a linear regression model with the logistic transformation of the response to the data of the following form:

$$\begin{aligned} \text{logit}(BCEF_{fr}) &= \log \frac{BCEF_{fr}}{1-BCEF_{fr}} \\ &= a_0 + a_1 \log A + a_2 \log SI + a_3 \log RS + a_4 A + a_5 RS + \varepsilon \end{aligned} \quad (3)$$

where  $BCEF_{fr}$  is the biomass conversion and expansion factor for the biomass fraction  $fr$  (stems, branches, foliage, roots), which is the ratio of the corresponding biomass fraction to the  $GSV$  ( $\text{t m}^{-3}$ );  $A$  is the average stand age in years;  $RS$  is the relative stocking (which is the ratio of the basal area of a stand to the basal area of a 'normal' stand, i.e., a fully stocked ideal stand based on national standards), typically scaled from 0 to 1 [21,22]);  $SI$  is the site index, which reflects the quality of a site and is expressed by the average height (m) of a mature forest (50 years old for birch and aspen, 160 years old for Siberian pine (*Pinus sibirica* Du Tour) and 100 years old for other species); and  $a_0$ – $a_5$  are model parameters. The residual  $\varepsilon$  is commonly assumed to have a Gaussian distribution with a zero mean and constant variance.

Equation (3) was selected after examining a number of different analytical expressions that would satisfy a set of general requirements (i.e., statistical significance, analysis of residuals, acceptability of the monotony of dependencies etc.). The logistic transformation of the response allows the BCEF to have values between 0 and 1, which fits the input data (i.e., the database contains values in the range of 0.02–0.95). In principle, Equation (3) can be generalized by replacing 1 with  $\max(BCEF)$ . In this case, the model will allow the response to lie between 0 and the maximum value.

Note that in contrast to classical allometry, Equation (3) allows for the occurrence of extrema by using  $A$  and  $RS$  twice on the right-hand side of the equation. Extreme BCEFs are not necessarily associated with the maximum (or minimum) values of  $A$  and  $RS$ . For example, the maximum amount of foliage is not necessarily observed in the densest forests, but rather in medium dense forests. It is known that the maximum mass of leaves on trees is reached at a middle age but not at a mature/overmature age.

A different set of coefficients was fitted for each major forest forming tree species of Northern Eurasia and the above-mentioned biomass fractions were calculated. We obtained a set of BCEF models for stems ( $BCEF_{st}$ ), branches ( $BCEF_{br}$ ), foliage ( $BCEF_{fol}$ ) and roots ( $BCEF_{ro}$ ) for tree species comprising

greater than 98% of the forest cover of Russia. The target variables ( $BCEF$ ,  $BEF$  and  $R:S$ ) were calculated as following.

$$BCEF = BCEF_{st} + BCEF_{br} + BCEF_{fol} + BCEF_{ro} \quad (4)$$

$$BEF = \frac{(BCEF_{st} + BCEF_{br} + BCEF_{fol})}{BCEF_{st}} \quad (5)$$

$$R : S = \frac{BCEF_{ro}}{(BCEF_{st} + BCEF_{br} + BCEF_{fol})} \quad (6)$$

where  $BCEF$  is the biomass conversion and expansion factor for the entire forest stand ( $t\ m^{-3}$ );  $BCEF_{fr}$  is the biomass conversion and expansion factor for the biomass fraction  $fr$  (stems, branches, foliage or roots); and  $R:S$  is the root-to-shoot ratio.

Due to non-normality and possible heteroscedasticity of the residuals, the model diagnostics and confidence intervals were obtained via non-parametric bootstrapping of 1000 random samples with replacement from the original data, refitting the model for each sample, and evaluating the means and quantiles of the resulting sets of 1000 parameter estimates. The RMSE (root mean squared error) was calculated to assess the accuracy of the model. Also, the species-specific mean percentage errors ( $MPEs$ ) were evaluated as follows:

$$MPE = 100\% \times \frac{1}{n} \sum_{i=1}^n \frac{(\hat{Y}_i - Y_i)}{Y_i}, \quad (7)$$

where  $Y_i$  and  $\hat{Y}_i$  are observed and estimated values respectively, and  $n$  is the total number of species-specific observations. The  $MPEs$  were thus evaluated for  $BCEF_{st}$ ,  $BCEF_{br}$ ,  $BCEF_{fol}$ ,  $BCEF_{ro}$ ,  $BCEF$ ,  $BEF$  and  $R:S$ . The overall  $MPEs$  for each of the above responses were evaluated as weighted averages of species with their respective areal map coverage as weights.

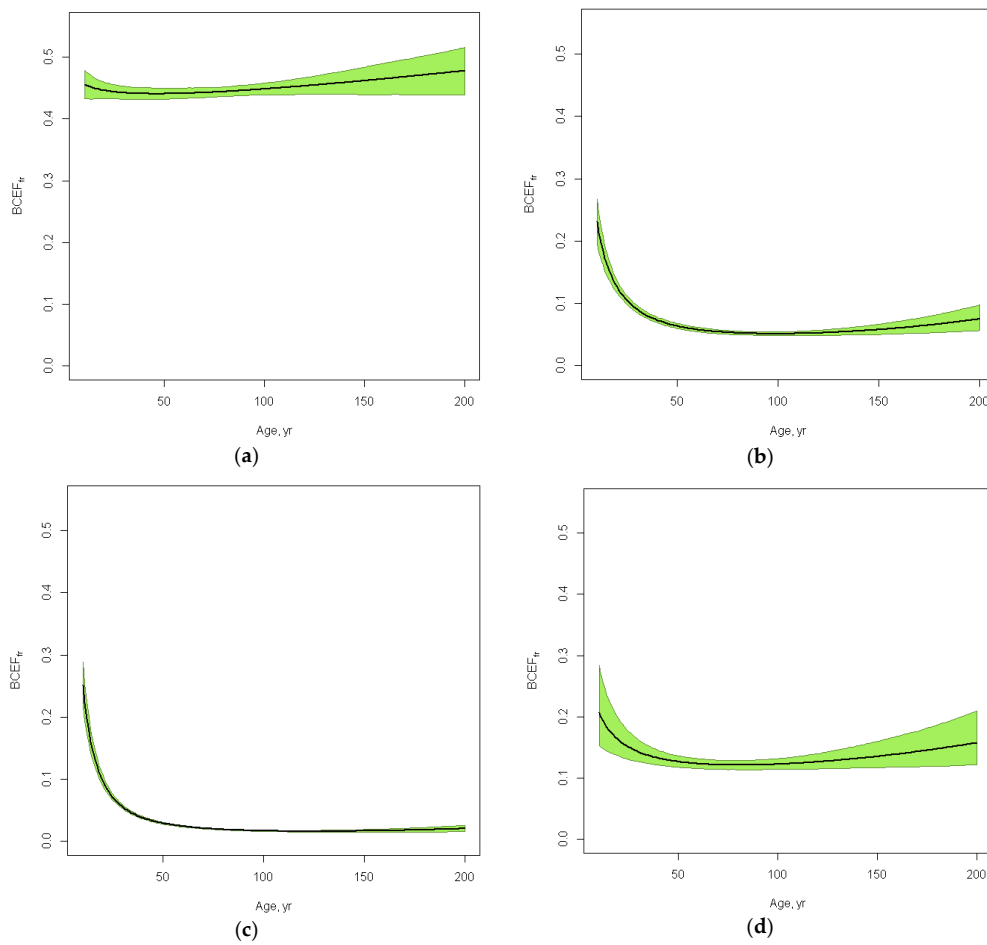
The estimated means and the associated confidence intervals for the maps were obtained by further bootstrapping. All analyses were carried out using R software [23], and an example of the code for fitting a model and producing the predictions is provided in the Appendix B.

### 2.3. Spatial Distribution of the Biomass Structure Parameters

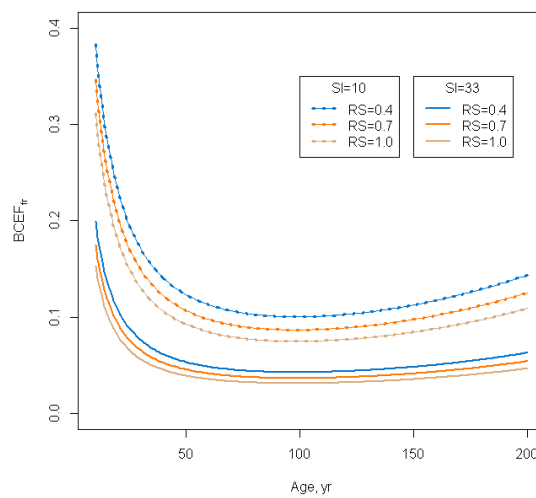
We used the Integrated Land Information System (ILIS) for Russia [11], which contains a land cover map [24,25] and associated forest data that are based on the SFR. The land cover map was developed using a multi-sensor remote sensing approach, geographically weighted regression and reference data obtained using Geo-Wiki [26]. The ILIS contains the spatial distribution of the forest parameters including the major tree species, the age, the relative stocking and site index, i.e., all the information needed to apply the regression models of forest biomass structure described above. From this, maps of the  $BCEFs$ ,  $BEFs$  and  $R:S$  values were produced. The uncertainties associated with the regression equations were also estimated. However, the “overall” uncertainties also depend on the accuracy of the ILIS and SFR, which were not considered here due to lack of information.

## 3. Results

Using the above-mentioned sample plot database, the parameters of Equation (3) were estimated for the major tree species in Northern Eurasia; these are presented in Table A1. Graphical examples of the equations with the associated 95% confidence envelopes are presented in Figures 1 and 2.



**Figure 1.** Estimated biomass conversion and expansion factors ( $BCEFs$ ) with confidence envelopes for (a) stem, (b) branches, (c) foliage and (d) roots in European Russia southern taiga pine forests depending on the stand age with a fixed  $SI = 21$  m and  $RS = 0.7$ . In order to build the regression models, we have used 1000 sample plots for stem biomass, 983—for branches, 1038—for foliage and 308—for roots.



**Figure 2.** Biomass conversion and expansion factor for branches in European Russia southern taiga pine forests for different relative stocking values (0.4, 0.7 and 1.0) and site indexes  $SI$  (10 m, 33 m). We have used 983 sample plots in order to build the regression model.

Stem *BCEFs*, which are, in essence, stem wood basic density or specific gravity, do not change much with age in the same site condition; they decrease slightly until the age of 50 and then increase for the remainder of the tree's life (Figure 1). *BCEFs* of other fractions (branches, foliage and roots) have a more noticeable drop from young to middle-aged forests because these fractions have a bigger share of young trees. Confidence intervals are wider for very young forests (where there are a variety of reforestation conditions) and for very old forests (where less measurements are available). The share of branches is higher in sparse and low productive forests (Figure 2).

In the next stage, we applied  $BCEF_{fr}$  equations to the ILIS land cover map with forest parameters. From this we obtained the spatial distribution of the live biomass structure indicators, including the *BCEFs* (Figure 3), the *BEFs* (Figure 4), and the *R:S* ratios (Figure 5). The maps have resolution of 5 arc second (or 150 m). They can be downloaded in GeoTiff format from Russian Forests and Forestry [27] [http://webarchive.iiasa.ac.at/Research/FOR/forest\\_cdrom/english/for\\_prod\\_en.html](http://webarchive.iiasa.ac.at/Research/FOR/forest_cdrom/english/for_prod_en.html).

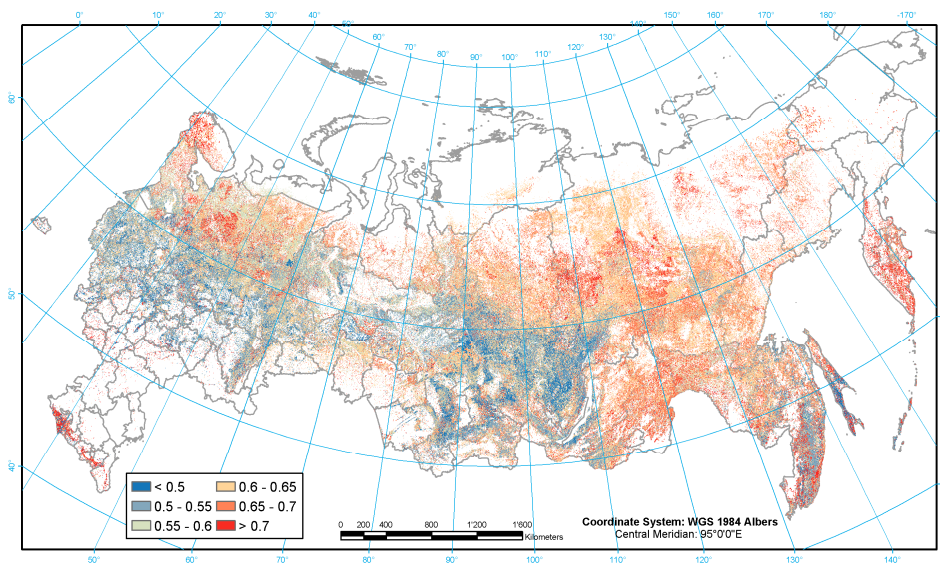


Figure 3. Geographical distribution of biomass conversion and expansion factors ( $BCEF$ ,  $t\ m^{-3}$ ).

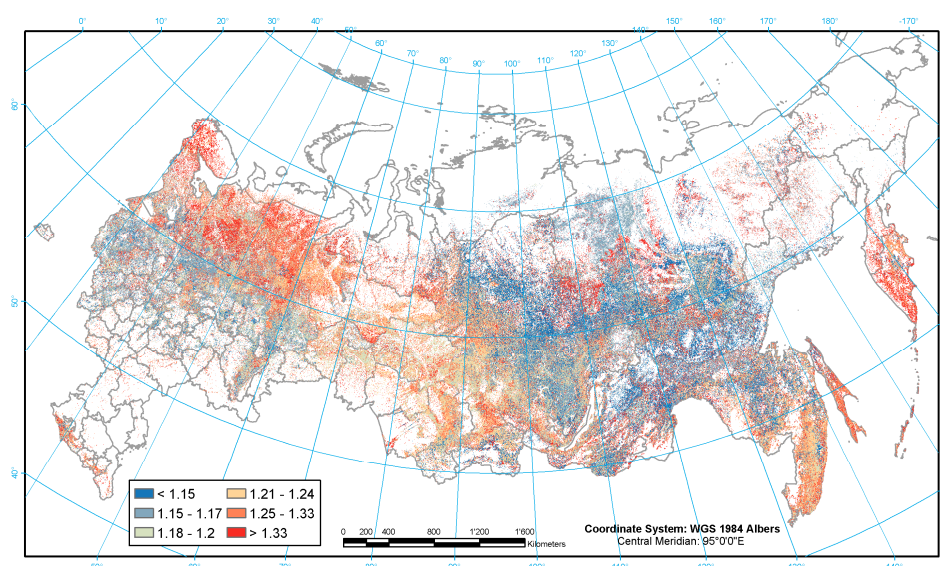
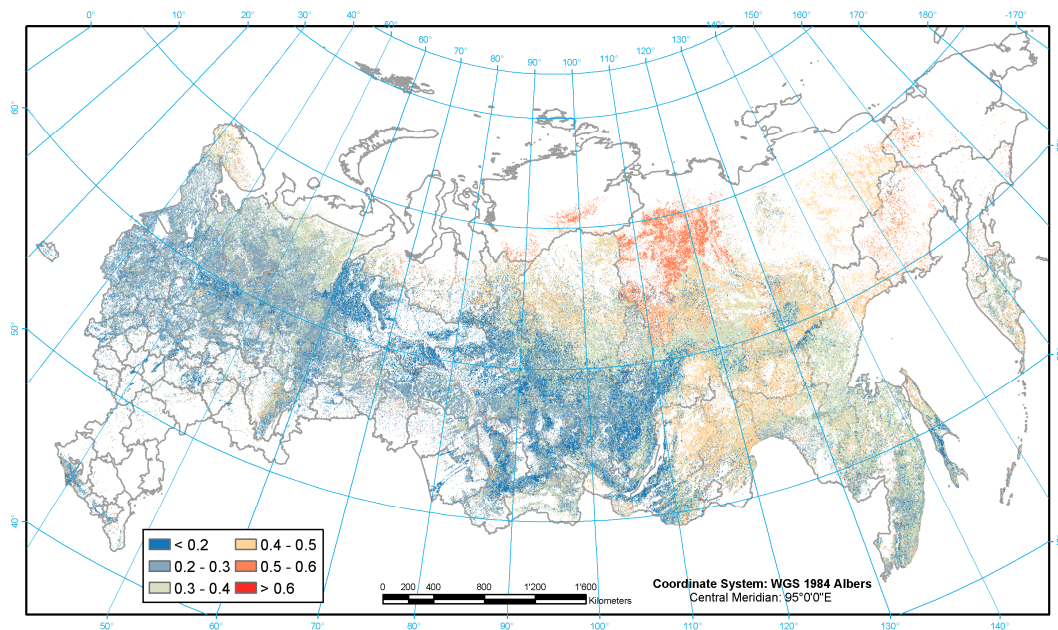


Figure 4. Geographic distribution of biomass expansion factors ( $BEF$ ).



**Figure 5.** Geographic distribution of the root-to-shoot ratios.

Relatively high values of the *BCEF* (Figure 3) for East Siberian forests are mostly related to larch forests with red areas indicating young forests (recently reforested burnt areas) and stone birch (*Betula ermanii Cham.*) in Kamchatka. The dark blue colors correspond mainly to boreal and temperate pine, spruce and aspen forests. Increased *BCEF* values in the southern European part of the study region are associated with birch, oak and beech forests. The northern European part of the study region also has relatively high *BCEF* values because of the dominance of either young or low productive forests.

The *BEF* is the greater, the large the proportion of branches and foliage in above-ground live biomass, which typical for young or sparse or low productive forests. High *BEF* values on the map (Figure 4) are also typical for Siberian pine, spruce and fir forests. Low values of *BEF* are associated with mature forests in general and with alder, pine and larch species in particular.

The *R:S* ratios are more homogenous across the map (Figure 5) in comparison to the *BEFs* and *BCEFs*. Overall the *R:S* ratios increase with the decreasing productivity of forests, particularly in harsh climates and poorer soil conditions. The highest share of belowground live biomass is observed in larch forests on the continuous permafrost of Central Siberia's high latitudes where the *R:S* ratios may reach 0.5–0.6 (including the most northern forests across the globe) while the highly productive forests of the southern taiga and temperate zone have a ratio of around 0.2.

The *MPEs* used to assess the accuracy of the models are shown in Table 1. The overall relative errors were found to be  $-0.6\%$ ,  $-1.0\%$  and  $11.6\%$  for *BCEF*, *BEF*, and *R:S* ratio respectively.

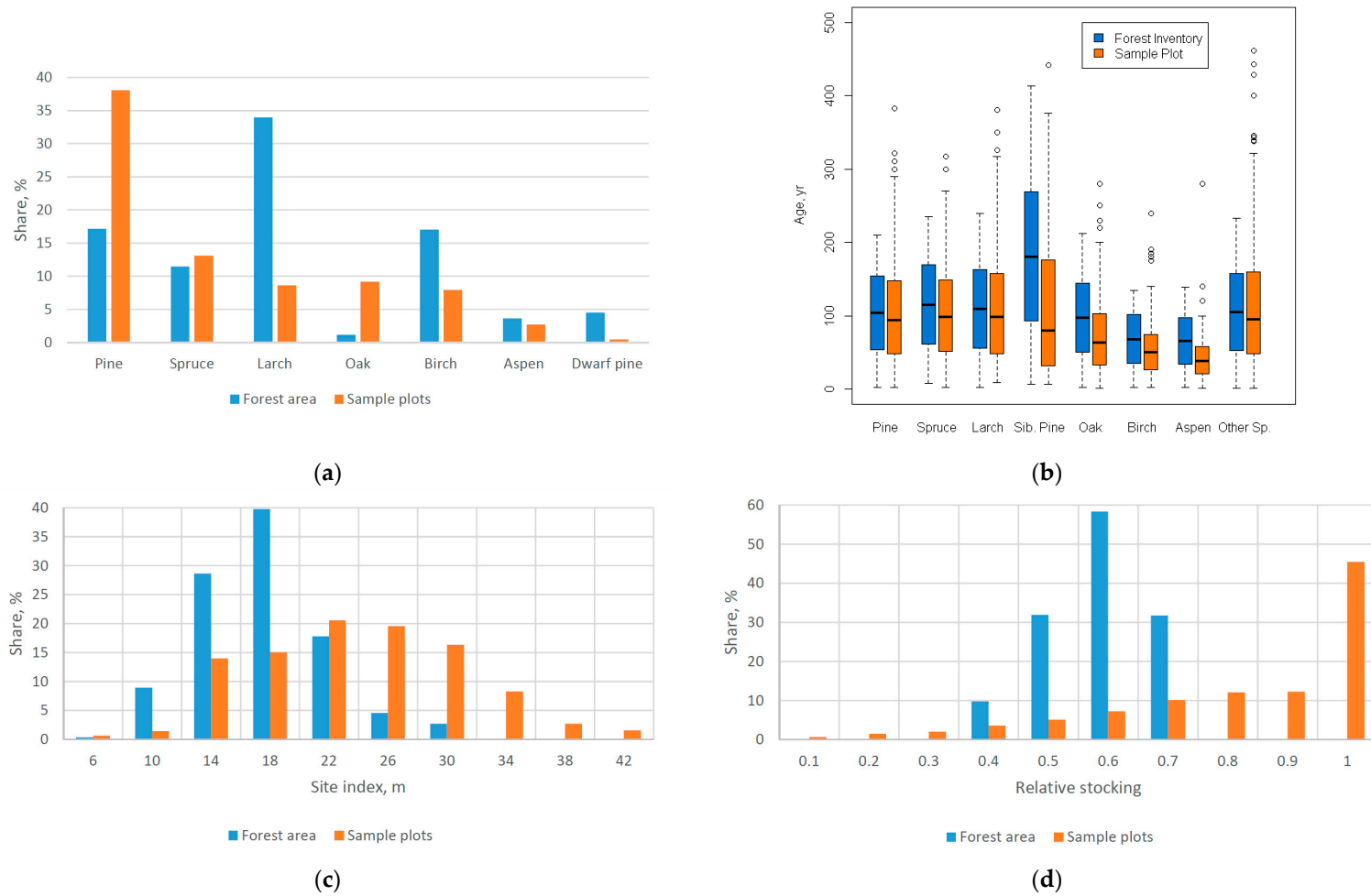


**Table 1.** Relative error of the models (%).

Species	Region/Zone	BCEF Stem	BCEF Branches	BCEF Foliage	BCEF Roots	BCEF	BEF	R:S
Pine	European middle taiga	2.4	7.7	6.3	7.9	1.4	−0.9	7.7
Pine	European southern taiga	3.0	23.7	11.5	10.6	−4.4	−1.1	13.6
Pine	European forest steppe	2.0	17.3	14.8	4.9	4.2	−1.5	0.1
Pine	Siberian middle taiga	1.3	10.5	12.0	8.4	−5.5	−0.9	−19.0
Pine	Siberian southern taiga	2.1	8.9	6.5	12.7	1.7	−0.6	12.7
Pine	Siberian forest steppe	2.3	10.7	10.7	12.3	1.2	−0.3	9.9
Spruce		2.2	14.7	18.4	10.6	0.5	−1.1	10.9
Fir		1.3	6.5	13.7	7.6	5.2	−1.2	5.0
Larch	middle taiga	2.3	17.1	25.8	20.9	−4.3	−1.1	10.5
Larch	southern taiga	2.6	10.0	16.1	10.4	3.2	−1.2	1.8
<i>Pinus sibirica</i>		2.4	17.5	12.5	3.2	2.2	−0.9	1.4
Oak		3.6	24.6	11.3	19.4	5.3	−1.3	22.6
Beech		2.2	15.0	5.2	8.7	2.5	−1.8	4.4
Hornbeam		1.1	30.7	16.2	19.2	−8.8	0.4	−18.2
Ash		1.1	50.0	27.6	19.2	−16.0	−1.5	−26.5
Birch	European Russia	1.4	11.3	22.4	6.7	−1.7	−1.2	7.2
Birch	Siberia	2.1	9.1	15.8	8.1	−0.5	−1.0	−12.9
Aspen	European Russia	1.8	14.5	13.4	8.7	−0.8	−0.3	8.4
Aspen	Siberia	2.2	8.5	5.2	12.1	6.8	−0.6	40.8
Grey alder		1.8	12.5	15.7	4.7	5.9	−0.1	−1.3
Black alder		0.7	14.2	12.0	4.8	−8.1	−0.7	16.8
Linden		0.8	10.7	6.6	20.3	6.2	−0.5	107.2
Poplar		2.2	25.0	34.8	0.5	6.7	2.0	−4.4
Total	SFR Russia	2.1	14.1	17.1	13.4	−0.6	−1.0	11.6

#### 4. Discussion

Accurate estimation of *BCEFs* with known uncertainties is crucial for GHG inventories and reporting. We applied a two-step approach: (1) build *BCEF* regression equations depending on the parameters available in both the measurements from sample plots and in the aggregated data from the SFR; (2) apply the regression equations to the SFR data and weight the *BCEF* by the *GSV*. The available database of forest biomass measurements is a collection of hundreds of individual studies performed without proper statistical design, which may lead to a bias in the observations. Some tree species were sampled much more intensively than others, and the distribution of forest parameters (e.g., age, tree density, site quality) is different in the available samples compared to the actual forests as reported in the SFR (Figure 6). This is the reason why attempts to use plot averages by tree species and regions by e.g., [16], and which is further implemented in the Russian national UNFCCC report 2017 [28] and in the guidelines [29] approved by the Russian Ministry of Natural Resources and Environment, introduce bias when applied to forest inventory data. Zamolodchikov et al. [16] did not consider two important factors of variability in the *BCEF*: tree density and the level of forest productivity. They assume that sample plots correctly represent the variety of Russian forests, which is not the case (Figure 6c,d). Therefore, the accuracy of the country's estimates based on the above-mentioned approach cannot be evaluated.



**Figure 6.** Discrepancy in sampling: (a) the amount of sample plots by dominant tree species, (b) the age by dominant tree species, (c) the distribution of sample plots by site index and (d) the relative stocking. Total amount of sample plots is 8007, forest area—763 million hectares.

In contrast, this study estimated the *BCEFs* considering the site index and the tree density distributions of Russian forests. This is why the accuracy of the estimation reported here corresponds to the territorial specifics of the forest cover, which are reflected by the forest inventory data. The total carbon pools and emissions obtained by the *BCEFs* from this study might (or might not) differ considerably from the current ones [28], but our *BCEF* models are generalizable, because, in addition to species, they take into account SI and RS composition.

A comparison of the *BCEFs* produced in this study with the ones calculated by Zamolodchikov et al. [16] is presented in the appendix (Table A3). Our estimates (Table A3) are higher for some tree species and biomass fractions (e.g., spruce and birch roots, aspen branches), but lower for others (e.g., Siberian pine and fir roots, spruce branches). For example, the difference (between our estimation and [16]) for the total stand live biomass *BCEF* of middle taiga middle-aged larch forests is only +9% (Table A3), while stem *BCEF* is −17%, branches are +69%, foliage is +37% and roots are +138%.

The IPCC 2003 [12] report suggests default *BEF* values (Table 2). Our results (GSV weighted averages) are considerably lower for both boreal and temperate zones. The difference in *BEF* estimation for boreal coniferous forests (Table 2) might not look substantial (1.35 versus 1.21, i.e., 11.6%); however, this leads to a difference in the live biomass estimation for the entire country of 3.9 million tons.

**Table 2.** Comparison of IPCC 2003 [12] Tier 1 default *BEFs* and our (GSV weighted average) estimates for Russia.

Zone	Forest Type	IPCC Default: Average <i>BEF</i> (Min–Max)	Estimates of This Study: Average <i>BEF</i> ±SD (Min–Max)
Boreal	conifers	1.35 * (1.15–3.80)	1.21 ± 0.003 (1.08–2.59)
	broadleaf	1.3 * (1.15–4.20)	1.21 ± 0.006 (1.07–2.87)
Temperate	conifers	1.3 * (1.15–4.20)	1.23 ± 0.005 (1.08–2.51)
	broadleaf	1.4 * (1.15–3.20)	1.23 ± 0.007 (1.07–1.70)

\*: the cited value is significantly (two standard deviation) higher than our estimate.

The default *BCEF* values recommended in the IPCC 2006 report are too high for the entire temperate zone due to the variation in Russian tree species and climate conditions across this zone (Table 3). Default *BCEF* values are also too high for forests with low growing stock (<20 m<sup>3</sup> ha<sup>−1</sup>), e.g., boreal forests at the northern or altitudinal limits, because they can include not only young forests but also sparse and low productive stands.

The Russian country report for FAO FRA 2015 [14] uses a Tier 1 approach to estimate above-ground biomass and Tier 2 for below-ground biomass (Table 4). Our approach satisfies the requirements of Tier 3: “Country-specific national or subnational biomass conversion expansion factors”.

**Table 3.** Comparison of *BCEF* ( $t\ m^{-3}$ ) default values from the IPCC 2006 report with *BCEFs* calculated using our approach.

Forest Type	Growing Stock Level ( $m^3\ ha^{-1}$ )									
	<20		21–50		51–100		>100		>200	
	IPCC	This Study $\pm$ SD	IPCC	This Study $\pm$ SD	IPCC	This Study $\pm$ SD	IPCC	This Study $\pm$ SD	IPCC	This Study $\pm$ SD
Boreal:										
pine	1.20 *	0.78 $\pm$ 0.04	0.68 **	0.74 $\pm$ 0.02	0.57 **	0.62 $\pm$ 0.01	0.50 **	0.53 $\pm$ 0.01	-	-
larch	1.22 *	0.81 $\pm$ 0.05	0.78 *	0.68 $\pm$ 0.01	0.77 *	0.65 $\pm$ 0.01	0.77 *	0.64 $\pm$ 0.01	-	-
fir and spruce	1.16 *	0.82 $\pm$ 0.02	0.66 **	0.77 $\pm$ 0.01	0.58 **	0.62 $\pm$ 0.01	0.53	0.53 $\pm$ 0.01	-	-
hard wood	0.90 *	0.76 $\pm$ 0.02	0.70	0.69 $\pm$ 0.01	0.62 **	0.68 $\pm$ 0.01	0.55 **	0.61 $\pm$ 0.01	-	-
Temperate:										
hard wood	3.00 *	0.74 $\pm$ 0.01	1.70 *	0.71 $\pm$ 0.01	1.40 *	0.70 $\pm$ 0.01	1.05 *	0.66 $\pm$ 0.01	0.80 *	0.65 $\pm$ 0.01
pine	1.80 *	0.86 $\pm$ 0.01	1.00 *	0.80 $\pm$ 0.02	0.75	0.71 $\pm$ 0.01	0.70 *	0.58 $\pm$ 0.01	0.70 *	0.52 $\pm$ 0.01
other conifers	3.00 *	0.79 $\pm$ 0.01	1.40 *	0.77 $\pm$ 0.01	1.00 *	0.70 $\pm$ 0.01	0.75 *	0.54 $\pm$ 0.01	0.70 *	0.49 $\pm$ 0.01

\*: the cited value is significantly (two standard deviation) higher than our estimate; \*\*: more than two standard deviation lower.

**Table 4.** Comparison of BEF, BCEF and R:S calculated using our approach with the FAO FRA country report [14].

Species	BEF		BCEF ( $t\ m^{-3}$ )		R:S	
	FRA	This Study $\pm$ SD	FRA	This Study $\pm$ SD	FRA	This Study $\pm$ SD
Pine	1.37 *	1.205 $\pm$ 0.004	0.58 *	0.541 $\pm$ 0.004	0.30 *	0.191 $\pm$ 0.005
Spruce	1.43 *	1.298 $\pm$ 0.006	0.57	0.559 $\pm$ 0.005	0.25 **	0.321 $\pm$ 0.012
Fir	1.35 *	1.274 $\pm$ 0.006	0.54 *	0.469 $\pm$ 0.005	0.20	0.178 $\pm$ 0.022
Larch	1.48 *	1.161 $\pm$ 0.007	0.77 *	0.640 $\pm$ 0.008	0.25 **	0.396 $\pm$ 0.039
Pine Siberian	1.46 *	1.236 $\pm$ 0.013	0.51 **	0.538 $\pm$ 0.012	0.25	0.235 $\pm$ 0.020
Oak	1.40 *	1.289 $\pm$ 0.014	0.81	0.783 $\pm$ 0.012	0.30	0.292 $\pm$ 0.025
Beech	1.35	1.263 $\pm$ 0.036	0.78	0.785 $\pm$ 0.026	0.30 *	0.213 $\pm$ 0.026
Birch	1.30 *	1.201 $\pm$ 0.006	0.66 *	0.636 $\pm$ 0.005	0.20 **	0.256 $\pm$ 0.011
Aspen	1.32 *	1.208 $\pm$ 0.018	0.53	0.528 $\pm$ 0.016	0.20 **	0.300 $\pm$ 0.037
Linden ( <i>Tilia</i> spp.)	1.35 *	1.185 $\pm$ 0.005	0.47 **	0.536 $\pm$ 0.004	0.20 **	0.376 $\pm$ 0.080
Total	1.41 *	1.214 $\pm$ 0.009	0.63 *	0.590 $\pm$ 0.008	0.25	0.288 $\pm$ 0.025

\*: the cited value is significantly (two standard deviation) higher than our estimate; \*\*: more than two standard deviation lower.

The R:S ratio suggested by Mokany et al. [30] overestimates the data for temperate coniferous forests (Table 5). A major reason for this is because most of the data used for averaging the R:S ratios were collected outside of Russia.

**Table 5.** Comparison of the root-to-shoot estimates calculated using our approach with other published values.

Vegetation Type	Shoot Biomass t/ha	R:S $\pm$ SD [30], IPCC 2006 [13]	IPCC, 2003	This Study
Boreal forest	<75	0.392 * $\pm$ 0.059	-	0.344 $\pm$ 0.021
	>75	0.239 $\pm$ 0.015	-	0.268 $\pm$ 0.009
Temperate conifer forest	<50	0.403 * $\pm$ 0.037	0.46 *	0.200 $\pm$ 0.011
	50–150	0.292 * $\pm$ 0.017	0.32 *	0.225 $\pm$ 0.007
Temperate oak forest	>150	0.201 $\pm$ 0.030	0.23 *	0.184 $\pm$ 0.006
	>70	0.295 $\pm$ 0.066	0.35 *	0.285 $\pm$ 0.023
Other temperate broadleaf forest	<50	0.456 * $\pm$ 0.062	0.43	0.390 $\pm$ 0.026
	50–150	0.226 ** $\pm$ 0.020	0.26	0.301 $\pm$ 0.018
	>150	0.241 $\pm$ 0.025	0.24	0.234 $\pm$ 0.017

\*: the cited value is significantly (two standard deviation) higher than our estimate; \*\*: more than two standard deviation lower.

All comparisons presented above relate only to trees in stands and they do not consider the lower layers of forest ecosystems (i.e., the understory and green forest floor). Russia has large areas of low productive (mostly northern) forests (around 45% of the area of the country's major forest forming tree species) where the share of live biomass of the lower layers is substantial (exceeding 10% of the total amount of LB) and should be accounted for within LB inventories. Such models have also been developed, but experimental data are poor and the uncertainties in the corresponding models are high. Even more important is the role of the lower layers of forest ecosystems in the assessments of the Net Primary Production of forests, particularly in methods based on the dynamics of LB components [5].

The BCEFs obtained in this study can be used (or tested) in neighboring regions. All available measurements, collected in Ukraine and Belarus, were also used in our regression analysis, so Equation (3) and its parameters (Table A2) are applicable to these two countries. However, regionalized GSV-weighted BCEFs, presented in the Tables 1–4 and Table A3, need to be calculated based on the forest inventory data of the countries.

## 5. Conclusions

This study offers a system of equations for estimating forest stand biomass structure and biomass expansion factors for Northern Eurasia, which are more systematic and have lower uncertainties compared to the currently used values for official reporting. The results are presented in the form of spatially distributed multidimensional equations, which use as much relevant information from the forest inventory as possible and are flexible enough that they can be used for different applications. The models are aggregated by species and regions, and satisfy the requirements of both national live biomass inventories and country reporting to international bodies such as the UNFCCC and FAO. The spatial distribution of the BEFs, BCEFs and the R:S ratios were developed based on regression equations and the actual characteristics of the forest cover. The resulting maps can be combined with different remote sensing products (e.g., [31]) and present spatially distributed information that can be used in further geographical analyses.

**Author Contributions:** D.S. performed the spatial analysis and wrote the draft of the paper. A.S. designed the study and contributed substantially to the writing of the paper. E.M. designed the statistical analysis and wrote the R-scripts. Y.D., V.B. and O.M. contributed to the statistical analysis. L.S. and F.K. contributed to the writing of the final version of the paper.

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**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A

**Table A1.** Average stand height (m) for different Site Indexes [22] Equation (1).

Site Index by M.M. Orlov	Birch (50 Years Old Seeding Origin)	Aspen, Poplar, Willow (50 Years, Vegetative Origin)	Siberian Pine (160 Years Old)	Other Species (100 Years Old)
If	34.7–37.5	39.5–42.5	56.3–60.4	49.3–52.9
Ie	31.8–34.6	36.4–39.4	52.0–56.2	45.6–49.2
Id	29.0–31.7	33.3–36.3	47.8–51.9	41.9–45.5
Ic	26.1–28.9	30.2–33.2	43.6–47.7	38.2–41.8
Ib	23.2–26.0	27.1–30.1	39.3–43.5	34.4–38.1
Ia	20.3–23.1	24.0–27.0	35.1–39.2	30.7–34.3
I	17.5–20.2	20.9–23.9	30.9–35.0	27.0–30.6
II	14.6–17.4	17.7–20.8	26.6–30.8	23.3–26.9
III	11.7–14.5	14.6–17.6	22.4–26.5	19.6–23.2
IV	8.9–11.6	11.5–14.5	18.1–22.3	15.9–19.5
V	6.0–8.8	8.4–11.4	13.9–18.0	12.2–15.8
Va	3.1–5.9	5.3–8.3	9.6–13.8	8.5–12.1
Vb	0.2–3.0	2.1–5.2	5.4–9.5	4.0–8.4

**Table A2.** Parameters of the forest live biomass from Equation (1).

Live Biomass Fraction	Equation (3) Parameter Estimation						$r^2$	RMSE	N
	$\hat{a}_0$	$\hat{a}_1$	$\hat{a}_2$	$\hat{a}_3$	$\hat{a}_4$	$\hat{a}_5$			
Pine (European middle taiga)									
Stem	1.3517	−0.1618	−0.1443	0.1995	0.0017	−0.5163	0.14	0.072	360
Branches	2.9767	−1.3238	−0.349	−0.4058	0.0117	−0.2093	0.58	0.039	365
Foliage	5.9603	−1.4686	−1.1163	0.0122	0.006	−0.5594	0.80	0.026	381
Roots	2.988	−0.589	−0.7742	−0.0521	0.0031	−0.5536	0.50	0.071	182
Pine (European southern taiga)									
Stem	0.7717	−0.0821	−0.2307	−0.0568	0.0017	−0.1335	0.09	0.079	1000
Branches	4.2451	−1.2431	−0.7691	−0.0037	0.0127	−0.5257	0.48	0.051	983
Foliage	6.6666	−1.8633	−1.0966	0.0253	0.0147	−0.3913	0.77	0.045	1038
Roots	1.5704	−0.5215	−0.5421	−0.1002	0.0064	−0.2413	0.25	0.079	308
Pine (European forest steppe)									
Stem	0.0915	0.095	−0.2237	−0.0149	−0.0002	−0.0021	0.07	0.069	356
Branches	4.535	−0.8482	−1.2881	0.074	0.0047	−0.216	0.52	0.052	393
Foliage	7.0673	−1.6427	−1.496	−0.1959	0.0112	−0.0959	0.79	0.057	423
Roots	−0.2385	−0.0587	−0.7152	−0.6812	−0.0009	0.5308	0.21	0.032	211
Pine (Siberian middle taiga)									
Stem	−0.1346	0.1184	−0.1981	−0.0839	−0.0011	−0.0372	0.12	0.054	158
Branches	1.0394	−0.3814	−0.5978	0.2721	0.0029	−1.1483	0.31	0.025	196
Foliage	7.8944	−1.4410	−1.5506	0.5492	0.0080	−1.5910	0.56	0.018	196
Roots	−3.2057	0.2113	−0.0074	−0.2885	−0.0032	0.0286	0.04	0.031	79
Pine (Siberian southern taiga)									
Stem	0.2432	0.1303	−0.2675	0.0493	−0.0013	−0.1730	0.13	0.066	586
Branches	1.1030	−0.8747	−0.3201	−0.6397	0.0066	0.0227	0.50	0.036	587
Foliage	5.5623	−1.7604	−0.9107	−0.7045	0.0102	0.0940	0.85	0.037	582
Roots	1.7253	−0.8490	−0.2326	0.2156	0.0095	−0.2221	0.19	0.092	301

Table A2. Cont.

Live Biomass Fraction	Equation (3) Parameter Estimation						$r^2$	RMSE	N	
	$\hat{a}_0$	$\hat{a}_1$	$\hat{a}_2$	$\hat{a}_3$	$\hat{a}_4$	$\hat{a}_5$				
Pine (Siberian forest steppe)										
Stem	1.1294	-0.0360	-0.4161	-0.2785	0.0005	0.0159	0.25	0.069	163	
Branches	5.1013	-0.5413	-1.6572	-0.8483	-0.0018	0.0194	0.64	0.065	164	
Foliage	8.1398	-1.5275	-2.1305	-1.5911	0.0056	0.8606	0.78	0.062	164	
Roots	1.7282	-0.7772	-0.2703	0.2559	0.0082	-0.3057	0.19	0.091	318	
Spruce										
Stem	-0.1933	0.1173	-0.1793	-0.0386	-0.0012	0.0010	0.08	0.065	740	
Branches	3.3337	-0.7691	-0.7772	0.2153	0.0029	-0.4646	0.47	0.066	767	
Foliage	5.9899	-1.5668	-0.8115	0.1443	0.0084	-0.6000	0.68	0.069	784	
Roots	1.0646	-0.4098	-0.4485	-0.2869	0.0042	-0.0946	0.41	0.080	401	
Fir										
Stem	0.0959	-0.0772	-0.0784	0.1718	0.0012	-0.1412	0.03	0.048	262	
Branches	2.3574	-0.7996	-0.6041	0.0848	0.0058	-0.3075	0.35	0.031	267	
Foliage	4.2704	-1.3153	-0.6861	-0.0233	0.0063	-0.3278	0.52	0.033	279	
Roots	0.6745	-0.5497	-0.3379	0.3682	0.0057	0.0503	0.38	0.032	68	
Larch (middle taiga)										
Stem	-1.3347	0.3120	0.0919	-0.1190	-0.0023	0.0842	0.07	0.078	228	
Branches	0.2162	-0.7587	0.0247	-0.4946	0.0028	0.0948	0.38	0.088	227	
Foliage	3.1846	-1.5464	-0.4319	-0.4693	0.0062	0.1521	0.58	0.046	236	
Roots	-2.5068	0.1744	-0.3284	-1.7051	-0.0023	1.4148	0.47	0.147	60	
Larch (southern taiga)										
Stem	1.1871	-0.2261	-0.1119	0.0403	0.0027	-0.1945	0.08	0.079	303	
Branches	4.2072	-1.4826	-0.6799	-0.5480	0.0118	0.2856	0.59	0.064	306	
Foliage	3.6928	-1.5604	-0.8472	-0.5441	0.0101	0.4642	0.61	0.033	313	
Roots	5.9509	-0.9601	-1.2220	0.3015	0.0098	-0.7839	0.51	0.062	93	
Cedar—Pinus sibirica										
Stem	-0.3297	-0.0292	0.1728	0.2949	0.0011	-0.5328	0.23	0.073	161	
Branches	5.3537	-1.0619	-0.5370	0.7861	0.0042	-2.2664	0.61	0.040	166	
Foliage	8.8813	-2.1237	-0.9001	0.3048	0.0120	-1.6325	0.86	0.057	166	
Roots	2.2189	-0.3527	-0.1341	1.1925	-0.0001	-2.2136	0.28	0.031	50	
Oak										
Stem	1.3658	-0.1909	-0.0649	0.0890	0.0026	-0.1504	0.02	0.096	462	
Branches	1.1424	-0.4008	-0.7627	-0.8207	0.0031	0.6612	0.13	0.094	456	
Foliage	4.1182	-1.2389	-1.1572	-0.4091	0.0061	0.1719	0.67	0.030	497	
Roots	4.8666	-0.8227	-1.2988	-0.8004	0.0056	0.6241	0.24	0.111	181	
Beech										
Stem	-0.8321	0.1425	0.2174	-0.2121	-0.0018	0.1649	0.04	0.078	177	
Branches	0.7318	0.0372	-0.7745	-0.3449	-0.0031	-0.0321	0.11	0.075	146	
Foliage	6.0548	-1.4001	-1.3849	-0.0755	0.0063	-0.6606	0.80	0.010	214	
Roots	1.3070	-0.3328	-0.6341	-0.8082	-0.0003	0.4298	0.17	0.073	112	
Hornbeam										
Stem	2.3347	0.3085	-0.2185	2.2934	-0.0042	-1.9967	0.40	0.057	38	
Branches	6.3469	-1.3749	-1.7074	0.1018	0.0345	0.7156	0.27	0.086	35	
Foliage	-1.6432	-1.0229	-0.7750	-3.5763	0.0118	3.4368	0.58	0.016	38	
Roots	4.6852	-0.7828	-1.2655	-0.7611	0.0050	0.6045	0.24	0.110	88	
Ash										
Stem	-1.4115	0.0959	0.6140	0.5147	-0.0024	-0.6225	0.20	0.058	60	
Branches	-3.1144	-0.4433	1.0840	0.5990	0.0033	-1.2218	0.14	0.090	60	
Foliage	5.7807	-1.8553	-0.9758	-0.1005	0.0178	-0.5541	0.63	0.100	66	
Roots	4.9038	-0.8047	-1.3065	-0.7893	0.0052	0.5818	0.24	0.110	85	
Birch (European Russia)										
Stem	-0.4434	0.1641	0.0579	-0.0112	-0.0037	-0.0682	0.07	0.059	376	
Branches	-0.2754	-0.4984	-0.3686	-0.5492	0.0063	0.2679	0.22	0.053	407	
Foliage	3.9489	-1.4559	-0.9133	0.7975	0.0174	-0.6793	0.52	0.026	421	
Roots	1.0270	-0.3507	-0.6383	-0.3961	-0.0015	0.3307	0.46	0.056	169	

Table A2. Cont.

Live Biomass Fraction	Equation (3) Parameter Estimation						$r^2$	RMSE	N
	$\hat{a}_0$	$\hat{a}_1$	$\hat{a}_2$	$\hat{a}_3$	$\hat{a}_4$	$\hat{a}_5$			
Birch (Siberia)									
Stem	0.2318	0.0500	-0.0543	0.0179	-0.0016	-0.0862	0.02	0.074	215
Branches	-0.7115	-0.4997	-0.2326	-0.6179	0.0081	0.4321	0.21	0.041	218
Foliage	0.0304	-1.0830	-0.4000	-0.7894	0.0104	0.6795	0.41	0.022	225
Roots	2.2132	-0.4646	-0.7980	-0.0893	0.0017	-0.0285	0.41	0.070	202
Aspen (European Russia)									
Stem	0.0203	0.0012	-0.0132	0.3453	-0.0006	-0.2399	0.02	0.062	110
Branches	0.2000	-0.2940	-0.0385	1.9673	0.0026	-1.7351	0.12	0.047	123
Foliage	3.6705	-1.3091	-0.9382	0.5383	0.0137	-0.7780	0.66	0.024	140
Roots	2.8964	-0.3984	-0.7258	0.5918	-0.0038	-0.9065	0.39	0.063	43
Aspen (Siberia)									
Stem	-1.2308	0.1325	0.2480	0.3622	0.0012	-0.1355	0.14	0.075	80
Branches	1.6460	-0.2113	-0.6766	0.9850	0.0021	-1.4918	0.22	0.029	70
Foliage	0.3332	-1.0598	-0.7049	-1.5391	0.0034	1.2358	0.80	0.010	80
Roots	1.9044	-0.7256	-0.7235	-1.3907	0.0036	0.8730	0.52	0.083	44
Grey alder									
Stem	-0.0936	-0.0586	-0.0101	-0.0269	0.0054	-0.1466	0.18	0.057	56
Branches	1.6014	-0.4444	-0.9354	0.5626	0.0070	-0.5702	0.33	0.068	63
Foliage	-2.0525	-1.5511	0.1970	-1.7943	0.0325	1.2196	0.72	0.016	62
Roots	-0.5188	-0.2344	-0.3283	-0.0381	0.0084	-0.3303	0.44	0.028	35
Black alder									
Stem	-0.4665	0.2482	-0.0978	0.1064	-0.0053	-0.1582	0.15	0.041	87
Branches	-0.7392	-0.3401	-0.4609	-0.1002	-0.0013	0.0418	0.14	0.018	90
Foliage	-0.3775	-1.1572	-0.3642	-1.2107	0.0067	0.8255	0.54	0.009	90
Roots	-0.5175	-0.2334	-0.3350	-0.0572	0.0083	-0.3157	0.44	0.028	35
Linden									
Stem	-0.5985	0.1141	0.0629	0.1274	-0.0003	-0.2424	0.29	0.038	248
Branches	-0.1664	-0.6651	-0.1371	-0.8517	0.0035	0.0990	0.46	0.027	254
Foliage	2.7459	-1.3151	-1.0017	-0.8749	0.0058	0.2103	0.77	0.011	258
Roots	2.6412	-0.3251	-1.0976	-0.5208	-0.0018	0.2377	0.38	0.051	30
Poplar									
Stem	-1.3420	0.3547	-0.2054	-0.6031	-0.0095	0.8033	0.49	0.063	89
Branches	-0.3045	-0.0037	-0.9988	-1.5338	-0.0163	1.4965	0.43	0.114	98
Foliage	-0.3746	-0.8670	-0.7316	-1.1603	-0.0010	1.7401	0.52	0.061	86
Roots	-0.6240	-0.6186	-0.1614	-0.8428	0.0058	1.1717	0.87	0.013	28



**Table A3.** Comparison of biomass conversion and expansion factors ( $t\ m^{-3}$ ) estimated in this study with those of Zamolodchikov et al. (2003).

Species	Zone	Age Group	BCEF ± SD Our Estimation					BCEF ± SD by Zamolodchikov et al. 2003				
			Stand	Stem	Branches	Roots	Foliage	Stand	Stem	Branches	Roots	Foliage
Pine	Northern taiga	Young	0.919 ± 0.034	0.490 ± 0.011	0.117 ± 0.008	0.178 ± 0.017	0.135 ± 0.012	0.937 ± 0.118	0.469 ± 0.021	0.128 ± 0.022	0.174 ± 0.031	0.167 * ± 0.044
		Middle-aged	0.715 ± 0.012	0.474 ± 0.006	0.064 ± 0.002	0.125 ± 0.006	0.051 ± 0.003	0.693 ± 0.023	0.468 ± 0.010	0.052 ** ± 0.002	0.143 * ± 0.009	0.030 ** ± 0.002
		Immature	0.667 ± 0.013	0.470 ± 0.006	0.058 ± 0.003	0.105 ± 0.006	0.034 ± 0.002	0.737 * ± 0.047	0.482 ± 0.016	0.067 * ± 0.010	0.155 * ± 0.016	0.033 ± 0.005
	Middle taiga	Mature	0.694 ± 0.013	0.484 ± 0.006	0.065 ± 0.003	0.115 ± 0.006	0.031 ± 0.002	0.661 ± 0.024	0.462 ± 0.008	0.057 ** ± 0.006	0.121 ± 0.008	0.021 ** ± 0.002
		Young	0.759 ± 0.030	0.452 ± 0.008	0.086 ± 0.008	0.123 ± 0.013	0.098 ± 0.012	0.793 ± 0.078	0.470 ± 0.027	0.131 * ± 0.026	0.108 ± 0.013	0.084 ± 0.014
		Middle-aged	0.644 ± 0.010	0.454 ± 0.005	0.054 ± 0.002	0.101 ± 0.005	0.035 ± 0.002	0.646 ± 0.018	0.455 ± 0.006	0.062 * ± 0.006	0.101 ± 0.004	0.028 ** ± 0.002
	Southern taiga	Immature	0.623 ± 0.011	0.454 ± 0.005	0.050 ± 0.002	0.093 ± 0.005	0.026 ± 0.001	0.715 * ± 0.052	0.475 ± 0.010	0.054 ± 0.006	0.162 * ± 0.033	0.024 ± 0.004
		Mature	0.611 ± 0.010	0.449 ± 0.005	0.052 ± 0.002	0.086 ± 0.004	0.024 ± 0.001	0.646 ± 0.028	0.478 * ± 0.014	0.054 ± 0.005	0.088 ± 0.004	0.027 * ± 0.004
		Young	0.725 ± 0.010	0.426 ± 0.003	0.092 ± 0.002	0.134 ± 0.006	0.074 ± 0.002	0.869 * ± 0.046	0.444 ± 0.008	0.112 * ± 0.007	0.190 * ± 0.019	0.123 * ± 0.012
	Middle-aged	Middle-aged	0.627 ± 0.005	0.434 ± 0.003	0.058 ± 0.001	0.109 ± 0.002	0.026 ± 0.001	0.703 * ± 0.027	0.447 ± 0.008	0.066 * ± 0.003	0.159 * ± 0.014	0.032 * ± 0.002
		Immature	0.618 ± 0.006	0.440 ± 0.003	0.051 ± 0.001	0.109 ± 0.003	0.019 ± 0.0001	0.658 * ± 0.021	0.453 ± 0.010	0.052 ± 0.002	0.128 ± 0.007	0.026 * ± 0.002
		Mature	0.633 ± 0.014	0.445 ± 0.006	0.053 ± 0.002	0.117 ± 0.007	0.018 ± 0.001	0.712 * ± 0.023	0.491 * ± 0.011	0.059 ± 0.004	0.137 ± 0.007	0.025 * ± 0.002
Spruce	Northern taiga	Young	0.971 ± 0.023	0.421 ± 0.006	0.163 ± 0.008	0.211 ± 0.010	0.175 ± 0.009	0.937 ± 0.068	0.413 ± 0.006	0.176 ± 0.020	0.159 ** ± 0.015	0.190 ± 0.027
		Middle-aged	0.815 ± 0.018	0.444 ± 0.006	0.107 ± 0.004	0.193 ± 0.010	0.071 ± 0.004	0.773 ± 0.039	0.457 ± 0.007	0.086 ** ± 0.010	0.138 ** ± 0.009	0.092 * ± 0.013
		Immature	0.816 ± 0.019	0.450 ± 0.007	0.104 ± 0.004	0.199 ± 0.011	0.063 ± 0.003	0.762 ± 0.039	0.457 ± 0.010	0.086 ** ± 0.009	0.150 ** ± 0.012	0.069 ± 0.008
	Middle taiga	Mature	0.779 ± 0.016	0.447 ± 0.006	0.082 ± 0.003	0.205 ± 0.010	0.046 ± 0.002	0.750 ± 0.039	0.457 ± 0.013	0.085 * ± 0.008	0.163 ** ± 0.015	0.045 ± 0.003
		Young	0.930 ± 0.022	0.409 ± 0.006	0.152 ± 0.007	0.198 ± 0.009	0.172 ± 0.009	0.937 ± 0.068	0.413 ± 0.006	0.176 * ± 0.020	0.159 ** ± 0.015	0.190 ± 0.027
		Middle-aged	0.729 ± 0.011	0.426 ± 0.004	0.084 ± 0.002	0.163 ± 0.006	0.055 ± 0.002	0.739 ± 0.038	0.430 ± 0.009	0.099 * ± 0.009	0.138 ** ± 0.009	0.072 * ± 0.012
	Southern taiga	Immature	0.718 ± 0.011	0.431 ± 0.004	0.076 ± 0.002	0.166 ± 0.006	0.045 ± 0.002	0.686 ± 0.026	0.465 * ± 0.010	0.057 * ± 0.004	0.122 ** ± 0.006	0.041 ± 0.006
		Mature	0.731 ± 0.013	0.436 ± 0.005	0.070 ± 0.002	0.186 ± 0.008	0.039 ± 0.001	0.681 ** ± 0.030	0.444 ± 0.010	0.060 * ± 0.003	0.139 ** ± 0.013	0.038 ± 0.004
		Young	0.837 ± 0.019	0.398 ± 0.005	0.126 ± 0.006	0.174 ± 0.009	0.140 ± 0.007	1.227 * ± 0.236	0.453 * ± 0.032	0.182 * ± 0.040	0.334 * ± 0.087	0.258 * ± 0.077
	Middle-aged	Middle-aged	0.683 ± 0.009	0.417 ± 0.004	0.072 ± 0.002	0.149 ± 0.005	0.046 ± 0.001	0.737 * ± 0.075	0.469 * ± 0.039	0.071 ± 0.009	0.140 ± 0.019	0.056 * ± 0.008
		Immature	0.675 ± 0.010	0.419 ± 0.004	0.067 ± 0.002	0.149 ± 0.005	0.040 ± 0.001	0.702 ± 0.038	0.437 ± 0.012	0.080 * ± 0.007	0.142 ± 0.013	0.043 ± 0.006
		Mature	0.676 ± 0.010	0.424 ± 0.004	0.059 ± 0.001	0.161 ± 0.006	0.032 ± 0.001	0.728 * ± 0.027	0.452 * ± 0.011	0.071 * ± 0.002	0.162 ± 0.011	0.042 * ± 0.003
Fir	all	Young	0.733 ± 0.046	0.371 ± 0.010	0.115 ± 0.010	0.112 ± 0.021	0.132 ± 0.014	0.840 ± 0.113	0.386 ± 0.033	0.123 ± 0.018	0.193 * ± 0.033	0.138 ± 0.028
		Middle-aged	0.554 ± 0.013	0.365 ± 0.005	0.067 ± 0.002	0.083 ± 0.010	0.046 ± 0.002	0.615 * ± 0.040	0.392 * ± 0.016	0.067 ± 0.010	0.109 * ± 0.009	0.047 ± 0.005
		Immature	0.530 ± 0.012	0.365 ± 0.004	0.061 ± 0.002	0.079 ± 0.011	0.036 ± 0.001	0.565 ± 0.034	0.348 ± 0.017	0.048 ** ± 0.003	0.131 * ± 0.011	0.037 ± 0.003
	Northern taiga	Mature	0.530 ± 0.014	0.370 ± 0.005	0.060 ± 0.002	0.082 ± 0.012	0.031 ± 0.001	0.539 ± 0.037	0.346 ** ± 0.010	0.055 ± 0.002	0.103 ± 0.024	0.035 * ± 0.001
		Young	1.016 ± 0.088	0.492 ± 0.016	0.153 ± 0.021	0.275 ± 0.057	0.096 ± 0.016	1.046 ± 0.063	0.481 ± 0.016	0.068 ** ± 0.013	0.456 * ± 0.025	0.042 ** ± 0.009
		Middle-aged	0.986 ± 0.054	0.547 ± 0.010	0.088 ± 0.007	0.323 ± 0.041	0.028 ± 0.003	0.845 ** ± 0.047	0.501 ** ± 0.017	0.057 ** ± 0.011	0.265 ± 0.015	0.023 ± 0.005
	Middle taiga	Immature	0.959 ± 0.047	0.559 ± 0.009	0.073 ± 0.004	0.309 ± 0.037	0.018 ± 0.001	0.900 ± 0.045	0.516 ** ± 0.013	0.054 ** ± 0.008	0.312 ± 0.021	0.019 ± 0.003
		Mature	0.926 ± 0.039	0.560 ± 0.008	0.062 ± 0.003	0.291 ± 0.030	0.013 ± 0.001	0.956 ± 0.044	0.531 ± 0.009	0.051 ** ± 0.006	0.359 ± 0.027	0.015 * ± 0.002
		Young	0.983 ± 0.081	0.494 ± 0.015	0.152 ± 0.020	0.247 ± 0.052	0.091 ± 0.016	0.811 ± 0.166	0.621 * ± 0.119	0.050 ** ± 0.016	0.111 ** ± 0.025	0.028 ** ± 0.012
	Southern taiga	Middle-aged	0.914 ± 0.042	0.550 ± 0.009	0.083 ± 0.005	0.259 ± 0.032	0.023 ± 0.002	0.836 ± 0.125	0.661 * ± 0.055	0.049 ± 0.007	0.109 ** ± 0.061	0.017 ± 0.001
		Immature	0.909 ± 0.041	0.563 ± 0.009	0.069 ± 0.003	0.262 ± 0.031	0.015 ± 0.001	0.867 ± 0.162	0.648 * ± 0.085	0.061 ± 0.007	0.131 ** ± 0.061	0.027 * ± 0.008
		Mature	0.888 ± 0.036	0.564 ± 0.008	0.060 ± 0.003	0.254 ± 0.027	0.011 ± 0.001	0.807 ± 0.095	0.632 * ± 0.029	0.055 ± 0.003	0.103 ** ± 0.061	0.017 * ± 0.002
Siberian pine	all	Young	0.985 ± 0.063	0.516 ± 0.012	0.157 ± 0.011	0.254 ± 0.046	0.057 ± 0.006	0.784 ** ± 0.087	0.494 ± 0.034	0.115 ** ± 0.019	0.136 ** ± 0.025	0.040 ** ± 0.008
		Middle-aged	0.735 ± 0.026	0.490 ± 0.007	0.062 ± 0.003	0.166 ± 0.018	0.017 ± 0.001	0.742 ± 0.112	0.524 * ± 0.047	0.055 ** ± 0.003	0.150 ± 0.061	0.013 ** ± 0.001
		Immature	0.696 ± 0.025	0.486 ± 0.008	0.048 ± 0.002	0.150 ± 0.016	0.012 ± 0.001	0.795 * ± 0.112	0.575 * ± 0.047	0.051 ± 0.003	0.156 ± 0.061	0.013 ± 0.001
	Northern taiga	Mature	0.754 ± 0.044	0.504 ± 0.012	0.053 ± 0.003	0.185 ± 0.032	0.011 ± 0.001	0.795 ± 0.099	0.575 * ± 0.030	0.051 ± 0.006	0.156 ± 0.061	0.013 ± 0.003
		Young	0.834 ± 0.081	0.414 ± 0.011	0.136 ± 0.007	0.191 ± 0.068	0.093 ± 0.005	0.783 ± 0.075	0.428 ± 0.028	0.101 ** ± 0.008	0.186 ± 0.028	0.068 ** ± 0.011
		Middle-aged	0.663 ± 0.024	0.426 ± 0.010	0.074 ± 0.005	0.135 ± 0.013	0.029 ± 0.002	0.682 ± 0.057	0.413 ± 0.022	0.056 ** ± 0.005	0.186 * ± 0.028	0.027 ± 0.003
	Middle taiga	Immature	0.653 ± 0.025	0.443 ± 0.013	0.065 ± 0.006	0.117 ± 0.010	0.028 ± 0.002	0.637 ± 0.054	0.393 ** ± 0.027	0.061 ± 0.007	0.156 * ± 0.016	0.027 ± 0.003
		Mature	0.663 ± 0.039	0.460 ± 0.020	0.062 ± 0.010	0.108 ± 0.015	0.033 ± 0.005	0.899 * ± 0.080	0.449 ± 0.031	0.106 * ± 0.013	0.29 * ± 0.031	0.045 * ± 0.005

Table A3. Cont.

Species	Zone	Age Group	BCEF ± SD Our Estimation					BCEF ± SD by Zamolodchikov et al. 2003					
			Stand	Stem	Branches	Roots	Foliage	Stand	Stem	Branches	Roots	Foliage	
Oak seeding	all	Young	1.165 ± 0.062	0.624 ± 0.013	0.167 ± 0.018	0.311 ± 0.038	0.063 ± 0.004	1.232 ± 0.137	0.569 ** ± 0.016	0.116 ** ± 0.009	0.485 * ± 0.104	0.062 ± 0.008	
		Middle-aged	0.966 ± 0.026	0.601 ± 0.008	0.137 ± 0.007	0.206 ± 0.016	0.022 ± 0.001	0.981 ± 0.060	0.594 ± 0.026	0.139 ± 0.016	0.230 ± 0.017	0.018 ** ± 0.002	
		Immature	0.967 ± 0.030	0.603 ± 0.010	0.142 ± 0.008	0.204 ± 0.018	0.018 ± 0.001	0.836 ** ± 0.081	0.585 ± 0.030	0.095 ** ± 0.033	0.147 ** ± 0.016	0.010 ** ± 0.002	
		Mature	0.989 ± 0.035	0.612 ± 0.011	0.150 ± 0.011	0.212 ± 0.020	0.017 ± 0.001	0.956 ± 0.120	0.580 ± 0.043	0.192 * ± 0.047	0.171 ± 0.027	0.013 ** ± 0.003	
Oak coppice	all	Young	1.453 ± 0.116	0.640 ± 0.021	0.229 ± 0.038	0.466 ± 0.070	0.118 ± 0.012	1.591 ± 0.104	0.671 ± 0.023	0.315 * ± 0.024	0.403 ± 0.040	0.201 * ± 0.017	
		Middle-aged	1.075 ± 0.042	0.611 ± 0.010	0.157 ± 0.011	0.269 ± 0.027	0.039 ± 0.002	1.082 ± 0.133	0.604 ± 0.031	0.126 ** ± 0.016	0.325 ± 0.083	0.026 ** ± 0.002	
		Immature	1.006 ± 0.034	0.603 ± 0.010	0.148 ± 0.008	0.230 ± 0.021	0.026 ± 0.001	1.125 * ± 0.179	0.615 ± 0.032	0.176 * ± 0.064	0.319 * ± 0.081	0.015 ** ± 0.001	
		Mature	0.979 ± 0.031	0.602 ± 0.010	0.143 ± 0.008	0.212 ± 0.018	0.021 ± 0.001	1.273 * ± 0.353	0.718 * ± 0.155	0.225 * ± 0.112	0.313 * ± 0.080	0.018 ** ± 0.005	
Other hard deciduous	all	Young	1.172 ± 0.052	0.601 ± 0.011	0.176 ± 0.018	0.333 ± 0.030	0.062 ± 0.005	1.248 ± 0.200	0.615 ± 0.066	0.186 ± 0.038	0.392 ± 0.079	0.056 ± 0.016	
		Middle-aged	1.008 ± 0.033	0.597 ± 0.009	0.151 ± 0.014	0.235 ± 0.015	0.025 ± 0.002	0.953 ± 0.058	0.610 ± 0.026	0.143 ± 0.018	0.185 ** ± 0.012	0.015 ** ± 0.001	
		Immature	1.021 ± 0.037	0.596 ± 0.010	0.158 ± 0.014	0.245 ± 0.020	0.022 ± 0.002	0.776 ** ± 0.079	0.527 ** ± 0.033	0.107 ± 0.018	0.129 ** ± 0.026	0.013 ** ± 0.003	
		Mature	1.046 ± 0.045	0.608 ± 0.012	0.166 ± 0.015	0.252 ± 0.026	0.020 ± 0.002	0.872 ** ± 0.060	0.545 ** ± 0.022	0.153 ± 0.018	0.165 ** ± 0.019	0.009 ** ± 0.001	
Birch	Northern taiga	Young	1.135 ± 0.066	0.534 ± 0.016	0.150 ± 0.014	0.366 ± 0.042	0.085 ± 0.012	0.922 ** ± 0.159	0.465 ** ± 0.030	0.121 ± 0.024	0.238 ** ± 0.088	0.099 ± 0.017	
		Middle-aged	0.976 ± 0.034	0.530 ± 0.009	0.116 ± 0.008	0.284 ± 0.021	0.046 ± 0.006	0.817 ** ± 0.119	0.561 ± 0.069	0.053 ** ± 0.021	0.180 ** ± 0.019	0.024 ** ± 0.011	
		Immature	0.909 ± 0.029	0.537 ± 0.009	0.103 ± 0.006	0.243 ± 0.019	0.026 ± 0.003	0.817 ** ± 0.105	0.542 ± 0.046	0.084 ** ± 0.025	0.152 ** ± 0.021	0.039 * ± 0.013	
	Middle taiga	Young	1.012 ± 0.042	0.528 ± 0.011	0.131 ± 0.009	0.287 ± 0.027	0.066 ± 0.007	0.922 ± 0.159	0.465 ** ± 0.030	0.121 ± 0.024	0.238 ± 0.088	0.099 * ± 0.017	
		Middle-aged	0.849 ± 0.017	0.534 ± 0.006	0.092 ± 0.004	0.198 ± 0.010	0.026 ± 0.002	0.875 ± 0.075	0.531 ± 0.013	0.103 ± 0.025	0.180 ** ± 0.019	0.060 * ± 0.018	
		Immature	0.801 ± 0.013	0.533 ± 0.006	0.084 ± 0.003	0.166 ± 0.007	0.018 ± 0.001	0.765 ± 0.053	0.532 ± 0.026	0.057 ** ± 0.003	0.152 ± 0.021	0.024 * ± 0.003	
	Southern taiga	Young	0.943 ± 0.031	0.524 ± 0.008	0.118 ± 0.006	0.244 ± 0.020	0.057 ± 0.004	0.873 ** ± 0.047	0.496 ± 0.011	0.121 ± 0.011	0.184 ** ± 0.015	0.022 ** ± 0.009	
		Middle-aged	0.806 ± 0.012	0.532 ± 0.005	0.083 ± 0.003	0.169 ± 0.006	0.022 ± 0.001	0.792 ± 0.024	0.539 ± 0.009	0.063 ** ± 0.003	0.169 ± 0.011	0.020 ± 0.001	
		Immature	0.767 ± 0.010	0.532 ± 0.005	0.076 ± 0.002	0.143 ± 0.005	0.016 ± 0.001	0.734 ± 0.033	0.536 ± 0.014	0.061 ** ± 0.004	0.123 ** ± 0.015	0.014 ± 0.001	
	Aspen	all	Young	0.866 ± 0.073	0.403 ± 0.015	0.093 ± 0.011	0.305 ± 0.054	0.065 ± 0.006	0.712 ** ± 0.110	0.388 ± 0.013	0.085 ± 0.016	0.179 ** ± 0.062	0.059 ± 0.020
			Middle-aged	0.733 ± 0.042	0.426 ± 0.012	0.080 ± 0.007	0.202 ± 0.027	0.025 ± 0.002	0.726 ± 0.089	0.463 * ± 0.019	0.063 ** ± 0.005	0.179 ± 0.062	0.020 ** ± 0.002
			Immature	0.686 ± 0.031	0.431 ± 0.010	0.070 ± 0.006	0.167 ± 0.019	0.017 ± 0.001	0.669 ± 0.114	0.432 ± 0.049	0.057 ** ± 0.006	0.168 ± 0.058	0.012 ** ± 0.002
Other soft deciduous	all	Young	0.815 ± 0.044	0.415 ± 0.009	0.106 ± 0.008	0.239 ± 0.032	0.055 ± 0.004	0.762 ± 0.077	0.552 * ± 0.060	0.063 ** ± 0.006	0.127 ** ± 0.008	0.020 ** ± 0.003	
		Middle-aged	0.732 ± 0.034	0.442 ± 0.005	0.077 ± 0.004	0.192 ± 0.027	0.020 ± 0.001	0.672 ± 0.046	0.486 * ± 0.030	0.047 ** ± 0.006	0.129 ** ± 0.008	0.011 ** ± 0.002	
		Immature	0.664 ± 0.022	0.450 ± 0.006	0.059 ± 0.004	0.142 ± 0.015	0.013 ± 0.001	0.667 ± 0.053	0.482 * ± 0.036	0.049 ** ± 0.003	0.121 ± 0.010	0.016 * ± 0.003	
Other soft deciduous	all	Young	0.682 ± 0.025	0.457 ± 0.005	0.064 ± 0.004	0.150 ± 0.019	0.011 ± 0.001	0.674 ± 0.032	0.482 * ± 0.016	0.049 ** ± 0.004	0.133 ± 0.009	0.010 ± 0.003	

\*: the cited value is significantly higher than our estimation, \*\*: it is significantly lower.

## Appendix B

### R Code for Regression Analysis

```

1.  —
2.  title: "Fraction Modeling"
3.  author: "Elena Moltchanova"
4.  date: "22 September 2017"
5.  —
6.
7.  "{r echo=F}
8.  # preliminaries
9.  rm(list=ls())
10. library(MASS)
11. setwd("C:/DM/Article/2018/BEF_RUS/")
12. dat <- read.csv("DB_plot.csv",header=T)
13. # Example of "DB_plot.csv", which extracted from Schepaschenko et al., 2017
14. # ID,SPEC_MOD,AGE,SI,RS,STEM,BRANCHES,FOLIAGE,ROOTS
15. #9436,102,50,32.53,1.47,0.365,0.03093,0.01963,0.02519
16.
17. # creating species list
18. species.list <- levels(dat[,2])
19. vars.list <- names(dat)[6:9]
20.
21. Nsim <- 10^3
22. Bsim <- 10^3
23.
24. # preparing the file for results
25. write.table(array(c('Species','Fraction','a0','a1','a2','a3','a4','a5',
26. 'a0.sd','a1.sd','a2.sd','a3.sd','a4.sd','a5.sd'),dim=c(1,14)),file='logit_bs_coefs_out.txt',quote=F,
27. row.names=F,col.names=F)
28.
29. # preparing array for predicted values
30.
31.
32. RS.val <- c(4,7,1.0)
33. SI.val <- t(array(
34. c(37.2, 24.4, 11.7,
35. 21.7, 13.1, 4.5,
36. 25.5, 16.1, 6.8,
37. 32.5, 21.4, 10.2),dim=c(3,4)))
38.
39. species.SI.grp <-
40. (substr(species.list,1,3)=="105")*1+(substr(species.list,1,3)%in%c("124","126","127"))*2+
41. (substr(species.list,1,3)%in%c("125","131"))*3
42. species.SI.grp[species.SI.grp==0] <- 4
43. #table(species.SI.grp,species.list)
44.

```

```

45. # FITTING LOGISTIC MODEL WITH BOOTSTRAP
46. Nsp <- length(species.list)
47.
48. for(j in 1:Nsp){
49.   dat.curr <- dat[dat[,2]==species.list[j],]
50.   for(k in 1:4){
51.     dat.curr$Y <- dat.curr[,5+k]
52.
53.     is.in.Y <- (!is.na(dat.curr$Y))&(!is.na(dat.curr$AGE))&(!is.na(dat.curr$SI))&(!is.na(dat.curr$RS))
54.
55.     if(sum(is.in.Y)!=0){
56.       boot.dat.curr <- dat.curr[is.in.Y,]
57.
58.       plot(boot.dat.curr$AGE,boot.dat.curr$Y,pch=1,lwd=2,ylim=c(0,1),
59.            xlim=c(0,210),xlab='Age',ylab='Fraction',
60.            main=paste('Species = ',species.list[j],', Variable = ', vars.list[k],sep=""))
61.
62.       co1b <- array(dim=c(Bsim,6))
63.
64.       for(biter in 1:Bsim){
65.         bootdat <- boot.dat.curr[sample(1:dim(boot.dat.curr)[1],replace=T),]
66.         m1b <- lm(log(Y/(1-Y)) ~log(AGE)+log(SI)+log(RS)+AGE+RS, data=bootdat)
67.
68.         co1b[biter,] <- m1b$coef
69.       }
70.       # estimating the mean from the coefs.
71.       mn1b <- apply(co1b,2,mean,na.rm=T)
72.       sd1b <- apply(co1b,2,sd,na.rm=T)
73.       AGE.val <- seq(10,210,10); n.age <- length(AGE.val)
74.       Y.mn1b <- Y.lo1b <- Y.hi1b <- array(dim=c(3,3,n.age))
75.       for(rs.i in 1:3){
76.         for(si.i in 1:3){
77.           for(m in 1:n.age){
78.             Y.sim <- 1/(1+exp(-(co1b[,1]+co1b[,2]*log(AGE.val[m])+
79.              co1b[,3]*log(SI.val[species.SI.grp[j],si.i])+co1b[,4]*log(RS.val[rs.i])+
80.              co1b[,5]*AGE.val[m]+co1b[,6]*RS.val[rs.i])))
81.             Y.mn1b[rs.i,si.i,m] <- mean(Y.sim,na.rm=T)
82.             Y.lo1b[rs.i,si.i,m] <- quantile(Y.sim,.025,na.rm=T)
83.             Y.hi1b[rs.i,si.i,m] <- quantile(Y.sim,.975,na.rm=T)
84.           }}}
85.
86.       ### adding non-parametric estimates for CI
87.
88.       # comparing CIs
89.       par(mfrow=c(1,1))
90.       plot(AGE.val,Y.mn1b[1,1,],pch=16,ty='o',xlab='age',ylab=expression(F[st]),ylim=c(0,1),
91.            main=paste("SI=",SI.val[species.SI.grp[j],1]))

```

```

92. polygon(c(AGE.val,AGE.val[n.age:1]),c(Y.lo1b[1,1,],Y.hi1b[1,1,n.age:1]),density=7,
93. angle=25,col='magenta',border='magenta')
94. lines(AGE.val,Y.mn1b[1,1,],pch=1,ty='o',col='magenta')
95.
96. write.table(array(c(species.list[j],vars.list[k],round(mn1b,4),round(sd1b,4)),dim=c(1,14)),
97. file='logit_bs_coefs_out.txt',quote=F,
98. row.names=F,col.names=F,append=T)
99.
100. }}}
101. ""
102.
103. \newpage
104. ## Estimated Coefficients for the Logit-linear model (Bootstrap)
105. ""{r echo=F}
106. t3 <- read.table('logit_bs_coefs_out.txt',header=T)
107. print(t3[,1:7])
108.
109. print(t3[,c(1:2,9:14)])
110. ""

```

## Acronyms

A	average stand age, years
AGB	aboveground oven-dry live biomass, $t\ ha^{-1}$
BCEF	Biomass Conversion and Expansion Factor, $t\ m^{-3}$
BEF	biomass expansion factor, dimensionless
DBH	average diameter at breast height, cm
GSV	growing stock volume, $m^3\ ha^{-1}$
ILIS	Integrated Land Information System
IPCC	Intergovernmental Panel on Climate Change
FAO FRA	Food and Agriculture Organization's Forest Resource Assessment
$M_{fr}$	live biomass of fraction $fr$ , $t\ ha^{-1}$
$M_{st}$	live biomass of stem wood and bark, $t\ ha^{-1}$
$M_{br}$	live biomass of tree branches, $t\ ha^{-1}$
$M_{fol}$	live biomass of tree foliage, $t\ ha^{-1}$
$M_{ro}$	live biomass of stem and roots, $t\ ha^{-1}$
RMSE	root mean squared error
R:S	root-to-shoot ratio
RS	relative stocking, typically scaled from 0 to 1—ratio of the basal area of a stand to the basal area of a 'normal' stand, i.e., a fully stocked ideal stand based on national standards [21,22]
SI	site index, which reflects the quality of a site and is expressed by the average height (m) of a mature forest (50 years old for birch and aspen, 160 years old for Siberian pine ( <i>Pinus sibirica</i> ) and 100 years old for other species); and $a_0$ – $a_5$ are model parameters.
SFR	Russian State Forest Register
UNFCCC	United Nations Framework Convention on Climate Change

## References

- Müller, A.; Weigelt, J.; Götz, A.; Schmidt, O.; Alva, I.L.; Matuschke, I.; Ehling, U.; Beringer, T. *The Role of Biomass in the Sustainable Development Goals: A Reality Check and Governance Implications*; IAS Working Paper; IASS: Potsdam, Germany, 2015; p. 36.
- Santoro, M.; Beaudoin, A.; Beer, C.; Cartus, O.; Fransson, J.E.S.; Hall, R.J.; Pathe, C.; Schmullius, C.; Schepaschenko, D.; Shvidenko, A.; et al. Forest growing stock volume of the northern hemisphere: Spatially explicit estimates for 2010 derived from Envisat ASAR. *Remote Sens. Environ.* **2015**, *168*, 316–334. [[CrossRef](#)]
- Shvidenko, A.Z.; Nilsson, S.; Stolbovoi, V.S.; Gluck, M.; Shchepashchenko, D.G.; Rozhkov, V.A. Aggregated estimation of the basic parameters of biological production and the carbon budget of Russian terrestrial ecosystems: 1. Stocks of plant organic mass. *Russ. J. Ecol.* **2000**, *31*, 371–378. [[CrossRef](#)]
- Shchepashchenko, D.; Shvidenko, A.; Nilsson, S. Phytomass (live biomass) and carbon of Siberian forests. *Biomass Bioenergy* **1998**, *14*, 21–31. [[CrossRef](#)]
- Shvidenko, A.; Schepaschenko, D.; Nilsson, S.; Bouloui, Y. Semi-empirical models for assessing biological productivity of Northern Eurasian forests. *Ecol. Model.* **2007**, *204*, 163–179. [[CrossRef](#)]
- Song, X.; Hoffman, F.M.; Iversen, C.M.; Yin, Y.; Kumar, J.; Ma, C.; Xu, X. Significant inconsistency of vegetation carbon density in CMIP5 Earth system models against observational data. *J. Geophys. Res. Biogeosciences* **2017**, *122*, 2282–2297. [[CrossRef](#)]
- Chave, J.; Réjou-Méchain, M.; Búrquez, A.; Chidumayo, E.; Colgan, M.S.; Delitti, W.B.C.; Duque, A.; Eid, T.; Fearnside, P.M.; Goodman, R.C.; et al. Improved allometric models to estimate the aboveground biomass of tropical trees. *Glob. Chang. Biol.* **2014**, *20*, 3177–3190. [[CrossRef](#)] [[PubMed](#)]
- Usoltsev, V. *Single-Tree Biomass Data for Remote Sensing and Ground Measuring of Eurasian Forests. CD-Version in English and Russian*; Ural State Forest Engineering University: Yekaterinburg, Russia, 2016; ISBN 978-5-94984-600-1.
- Forrester, D.I.; Tachauer, I.H.H.; Annighofer, P.; Barbeito, I.; Pretzsch, H.; Ruiz-Peinado, R.; Stark, H.; Vacchiano, G.; Zlatanov, T.; Chakraborty, T.; et al. Generalized biomass and leaf area allometric equations for European tree species incorporating stand structure, tree age and climate—ScienceDirect. *For. Ecol. Manag.* **2017**, *396*, 160–175. [[CrossRef](#)]
- Usoltsev, V.A.; Chasovskikh, V.P.; Noritsina, Y.V.; Noritsin, D.V. Allometric Models of Tree Biomass for Airborne Laser Scanning and Ground Inventory of Carbon Pool in the Forests of Eurasia: Comparative Analysis. *Sib. J. For. Sci.* **2016**, *3*, 68–76. [[CrossRef](#)]
- Gordov, E.P.; Bryant, K.; Bulygina, O.N.; Csiszar, I.; Eberle, J.; Fritz, S.; Gerasimov, I.; Gerlach, R.; Hese, S.; Kraxner, F.; et al. Development of Information-Computational Infrastructure for Environmental Research in Siberia as a Baseline Component of the Northern Eurasia Earth Science Partnership Initiative (NEESPI) Studies. In *Regional Environmental Changes in Siberia and Their Global Consequences*; Springer Environmental Science and Engineering; Springer: New York, NY, USA, 2013; pp. 19–56. ISBN 978-94-007-4569-8.
- Intergovernmental Panel on Climate Change (IPCC). *Good Practice Guidance for Land Use, Land-Use Change and Forestry*; Institute for Global Environmental Strategies: Kanagawa Prefecture, Japan, 2003.
- Intergovernmental Panel on Climate Change (IPCC). *2006 IPCC Guidelines for National Greenhouse Gas Inventories*; IGES: Hayama, Japan, 2006; ISBN 4-88788-032-4.
- Food and Agriculture Organization (FAO). *Russian Federation—Global Forest Resources Assessment 2015—Country Report*; Global Forest Resources Assessment Country Reports; FAO: Rome, Italy, 2014.
- Alexeyev, V.A.; Birdsey, R.A. *Carbon Storage in Forests and Peatlands of Russia*; General Technical Report NE-244; USDA, Forest Service, Northeast Research Station: Radnor, PA, USA, 1998.
- Zamolodchikov, D.G.; Utkin, A.I.; Chestnych, O.V. Biomass conversion and expansion factors for major forest forming species in Russia. *For. Mensurat. For. Invent.* **2003**, *1*, 119–127. Available online: [http://old.cepl.rssi.ru/publication/s/pub\\_lab1/zamolodchikov%2003%20koefficienty%20konversii%20zapasov%20v%20fitomassu.pdf](http://old.cepl.rssi.ru/publication/s/pub_lab1/zamolodchikov%2003%20koefficienty%20konversii%20zapasov%20v%20fitomassu.pdf) (accessed on 25 May 2018).
- Usoltsev, V.A. *Growth and Structure of Forest Live Biomass*; Nauka: Novosibirsk, Russia, 1988; ISBN 5-02-028865-9.
- Usoltsev, V.A. *Forming Databanks about Live Biomass of Forests*; Russian Academy of Sciences: Ekaterinburg, Russia, 1998; ISBN 5-7691-0832-0.
- Usoltsev, V.A. *Forest Biomass of Northern Eurasia: Mensuration Standards and Geography*; Ural Branch of RAS: Yekaterinburg, Russia, 2002; ISBN 5-7691-1278-6.

20. Usoltsev, V.A. *Biological Productivity of North Eurasian Forests: Methods, Database and Its Applications*; Ural Branch of Russian Academy of Science: Ekaterinburg, Russia, 2007; ISBN 5-7691-1757-5.
21. Schepaschenko, D.; Shvidenko, A.; Usoltsev, V.; Lakyda, P.; Luo, Y.; Vasylyshyn, R.; Lakyda, I.; Myklush, Y.; See, L.; McCallum, I.; et al. A dataset of forest biomass structure for Eurasia. *Sci. Data* **2017**, *4*, 170070. [[CrossRef](#)] [[PubMed](#)]
22. Shvidenko, A.Z.; Schepaschenko, D.G.; Nilsson, S.; Buluy, Y.I. *Tables and Models of Growth and Productivity of Forests of Major Forest Forming Species of Northern Eurasia. Standard and Reference Materials*, 2nd ed.; Federal Agency of Forest Management: Moscow, Russia, 2008.
23. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2013.
24. Schepaschenko, D.; McCallum, I.; Shvidenko, A.; Fritz, S.; Kraxner, F.; Obersteiner, M. A new hybrid land cover dataset for Russia: A methodology for integrating statistics, remote sensing and in situ information. *J. Land Use Sci.* **2011**, *6*, 245–259. [[CrossRef](#)]
25. Schepaschenko, D.; Shvidenko, A.Z.; Lesiv, M.Y.; Ontikov, P.V.; Shchepashchenko, M.V.; Kraxner, F. Estimation of forest area and its dynamics in Russia based on synthesis of remote sensing products. *Contemp. Probl. Ecol.* **2015**, *8*, 811–817. [[CrossRef](#)]
26. See, L.; Fritz, S.; Perger, C.; Schill, C.; McCallum, I.; Schepaschenko, D.; Duerauer, M.; Sturn, T.; Karner, M.; Kraxner, F.; et al. Harnessing the power of volunteers, the internet and Google Earth to collect and validate global spatial information using Geo-Wiki. *Technol. Forecast. Soc. Chang.* **2015**, *98*, 324–335. [[CrossRef](#)]
27. Shvidenko, A.; Schepaschenko, D.; McCallum, I.; Nilsson, S. Russian Forests and Forestry. Available online: [http://www.iiasa.ac.at/Research/FOR/forest\\_cdrom](http://www.iiasa.ac.at/Research/FOR/forest_cdrom) (accessed on 25 May 2018).
28. Nakhutin, A.I.; Gitarskii, M.L.; Romanovskaya, A.A.; Ginzburg, V.A.; Govor, I.L.; Grabar, V.A.; Imshennik, E.V.; Karaban', R.T.; Korotkov, V.N.; Uvarova, N.E.; et al. *National Report on the Cadastre of Anthropogenic Emissions from Sources and Absorptions by Sinks of Greenhouse Gases of Russian Federation Not Regulated by Montreal Protocol for 1990–2015*; Institute of Global Climate and Ecology of the Federal Service for Hydrometeorology and Environmental Monitoring and the Russian Academy of Sciences: Moscow, Russia, 2017; p. 471.
29. *Guideline for Quantification of Greenhouse Gas Absorption*; Ministry of Natural Resources and Environment of the Russian Federation: Moscow, Russia, 2017.
30. Mokany, K.; Raison, R.J.; Prokushkin, A.S. Critical analysis of root: Shoot ratios in terrestrial biomes. *Glob. Chang. Biol.* **2006**, *12*, 84–96. [[CrossRef](#)]
31. Santoro, M.; Beer, C.; Cartus, O.; Schmullius, C.; Shvidenko, A.; McCallum, I.; Wegmüller, U.; Wiesmann, A. Retrieval of growing stock volume in boreal forest using hyper-temporal series of Envisat ASAR ScanSAR backscatter measurements. *Remote Sens. Environ.* **2011**, *115*, 490–507. [[CrossRef](#)]



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