

## Article

# Species Composition Affects the Accuracy of Stand-Level Biomass Models in Hemiboreal Forests

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**Abstract:** Various tree species contribute differently to total biomass stock, making the development of species-specific stand-level equations critical for better estimation of forest biomass and quantification of carbon stocks. Previously derived dry weight biomass models did not assess the effect of dominant species composition according to stand growing stock. Growing stock definitions and forest species composition differ by country, justifying the need for national stand-level biomass equations. We explored the relationship between growing stock volume and stand biomass density of above- and below-ground components in six common forest categories in Latvia using plot-level data from the National Forest Inventory from 2016 to 2020. Additionally, we explored model dependence on region, forest type, and species composition index. Models that considered growing stock and dominant species composition index performed better than models with growing stock as the only variable, especially for heterogeneous deciduous forests with greater species diversity. The elaborated models are a useful alternative to individual-level assessment for estimating forest biomass stocks in circumstances where individual tree data are not available.



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**Keywords:** composition index; forest biomass; National Forest Inventory; biomass density; growing stock

## 1. Introduction

The increasing attention on the role of the forestry sector in reducing the amount of CO<sub>2</sub> in the atmosphere and storing carbon in forest biomass requires continuously updated information on the condition of forests and their development [1–3]. Total forest biomass is an important factor in carbon balance modeling [4–7]. National Forest Inventory (NFI) data are the main source of information for international programs and statistics, such as the Forest Resource Assessment Program for the Food and Agriculture Organization (FAO) and the national greenhouse gas inventory report for the Land Use, Land-Use Change, and Forestry sector under the United Nations Framework Convention on Climate Change. The importance of NFI data in estimating forest biomass and carbon stocks is widely accepted and recognized [3,8,9].

Allometric relationships between above- and below-ground biomass components and stand characteristics are highly variable by species, stand growing stock [10–12], stand age [9–13], aridity [10], site [14,15], and other factors [16,17]. Considering this, the extrapolation of existing biomass models can lead to divergent biomass estimates, justifying the need for national and site-specific equations [18,19].

Forest stand biomass calculation can be carried out using allometric equations with individual tree or stand attributes, biomass expansion factors, and various remote sensing techniques, which are the key tools to improve forest biomass estimation on a broader scale [20,21]. Using stand attributes is more common in practical forestry since the plot data are not always available to forest owners and companies who want to assess the contribution of their forests to the total carbon stock. In ecological studies, such parameters

as biomass are not easily measured directly; therefore, national biomass equations are created. Regionally, equations based on extensive and representative material for the prediction of above- and below-ground biomass components of individual trees of Scots pine, Norway spruce, birch, European aspen, common alder, and grey alder have recently been adapted in Latvia [22,23]. The obtained equations are the only ones available for larger-scale estimation of above- and below-ground biomass components across the region between boreal and temperate forests. However, stand-level biomass models are still not available.

The territory of Latvia is located in the European hemiboreal forest zone [24], where coniferous species are mixed with fast-growing broad-leaved species [25]. According to 2021 NFI data, the most widespread and commercially valuable tree species in Latvia are Scots pine (*Pinus sylvestris* L.), birch (mainly silver birch (*Betula pendula* Roth)), and Norway spruce (*Picea abies* [L.] Karst), which contribute 32.7%, 23.6%, and 20.0% of the total growing stock volume, respectively. Species that account for the remaining 21.3% of the growing stock are European aspen (*Populus tremula* L., 9.3%), common alder (*Alnus glutinosa* (L.) Gaertn., 6.3%), and grey alder (*Alnus incana* (L.) Moench., 5.8%).

In Latvia and the European hemiboreal forest zone as a whole, knowledge of factors influencing stand-level forest biomass appraisals based on inventories is limited. There is a need for reliable algorithms to obtain accurate estimates of forest biomass if individual tree data are unavailable. The objective of this study is to develop stand-level biomass models for six common species-based forest categories in Latvia's forests. We hypothesize that derived biomass appraisals for above- and below-ground stand components are influenced by the factors of region, forest type, and species composition. Specifically, our objectives were to (I) investigate the relationship between species-based forest category biomass and stand characteristics, (II) study the dependence of the stand-level models on region, forest type, and species composition index, and (III) assess the suitability of the developed equations for national forest biomass estimates in Latvia.

## 2. Materials and Methods

In Latvia, information about forest resources and their dynamics has been obtained via the NFI since 2003. In the present study, data from the Latvian NFI from 2016 to 2020 were used to derive stand-level biomass models for forest categories dominated by tree species common to Latvia. The dominance of a tree species was determined as a proportion of the growing stock in the sample plot in relation to other tree species. The NFI uses a  $4 \times 4$  km grid across Latvia with 4 permanent  $500 \text{ m}^2$  sample plots at each grid point. In total, 16,157 plots are spread throughout the territory of Latvia, and each individual plot is measured once every 5 years [26]. According to the data (NFI 2016–2020), forest land covers 3.24 million ha (52%) of Latvia, with a total growing stock of 682.3 million  $\text{m}^3$ .

The stem volume of a tree in the Latvian NFI is defined as the volume of stem wood over bark above the stump, including the top of a tree. The total volume of growing stock includes the individual stem volumes of all living trees with a minimum diameter at breast height (DBH) of 2.1 cm. The calculation of growing stock is carried out using species-specific models developed by Liepa [27]. Above- and below-ground dry weight biomass components of Scots pine, Norway spruce, birch, European aspen, common alder, and grey alder were computed through species-specific allometric models [22,23]. Total tree biomass was calculated at the plot level by summing the tree biomass of the individuals within the plot. These models predict stem volume and tree component biomass using DBH and tree height (H) as explanatory variables.

If an individual NFI plot contains more than one land use category, it is divided into smaller units referred to as sectors. Because sector size varied, the growing stock and biomass were converted to a per hectare basis. For the development of stand-level biomass models, only the plots or sectors with an area of at least  $400 \text{ m}^2$  were selected, assuming they contained an adequate distribution of trees. This was done to avoid unusual observations, such as sample plots at the side of a river or field that could lead to undesirable outliers.

We used NFI data for the land categories of forest land and afforested agricultural land. Ultimately, data from 6530 NFI plots met the selection criteria and were used for stand-level biomass assessment (Table 1). In Latvian forests, two tree-like birch species—silver birch (*Betula pendula* Roth) and downy birch (*Betula pubescens* Ehrh.)—are not distinguished in the forest inventory registers; therefore, we used the general term birch and did not distinguish between them.

**Table 1.** Descriptive statistics of data used to develop stand-level biomass models.

Species-Based Forest Category	NFI Plots	GS, m <sup>3</sup> ha <sup>-1</sup>	AGB, t ha <sup>-1</sup>	BGB, t ha <sup>-1</sup>	SB, t ha <sup>-1</sup>	BB, t ha <sup>-1</sup>
		Average (Min–Max)	Average (Min–Max)	Average (Min–Max)	Average (Min–Max)	Average (Min–Max)
Scots pine	1838	265.8 (0.1–958.5)	143.7 (0.1–456.4)	35.2 (0.1–111.3)	112.4 (0.1–403.6)	28 (0.1–124.2)
Norway spruce	1231	224.4 (0.1–832.2)	128 (0.2–398.8)	35.5 (0.1–112.6)	89.9 (0.1–321.1)	34.2 (0.2–96.2)
Birch	1800	182.9 (0.1–776.4)	105.5 (0.1–427.5)	28.6 (0.1–114)	84.3 (0.1–352.1)	21 (0.1–91.9)
European aspen	513	231.1 (0.1–1015.2)	114.6 (0.1–483.9)	28 (0.1–100.7)	90.8 (0.1–404.2)	21.3 (0.1–80.8)
Grey alder	582	123.6 (0.1–494.3)	61.7 (0.1–248.8)	16.5 (0.1–63.3)	50.4 (0.1–215.2)	11.8 (0.1–75.4)
Common alder	396	210.3 (0.1–1035.6)	108.9 (0.1–494.8)	28.1 (0.1–88)	91.7 (0.1–484.6)	17.2 (0.1–53.8)
Other	170	173.4 (0.1–731.8)	90.9 (0.1–319.1)	30.3 (0.1–182.2)	68.1 (0.1–238.8)	32.4 (0.2–136.0)

We determined the relationships between stand age, DBH, H, stand basal area (G), growing stock (GS), and stand biomass components (total above-ground biomass (AGB), total below-ground biomass (BGB), stem biomass (SB), and branch biomass (BB) using Spearman's correlation.

The single variable nonlinear mixed-effects function “nlmer” from the lme4 package in R statistical software [28] was fitted to the stand biomass data to analyze the sources of variation in biomass components. In this model (Equation (1)), forest stand AGB, BGB, SB, and BB estimates were predicted as a function of stand variables as a fixed effect, while the region, forest type, and species composition division were accounted for separately as random effects:

$$Y_{rsc} = a * X_{rsc}^{b_1 + u_r} + \varepsilon_{rsc}, \quad (1)$$

where  $Y_{rsc}$  is the observed stand biomass component of the target species (t),  $X$  is the stand fixed effect variable,  $a$  and  $b_1$  are parameters, and  $u_r$  is the stand random effect variable assigned to the  $b_1$  parameter. The subscripts  $r$ ,  $s$ , and  $c$  refer to the random effect (region, forest type, or species composition index), stand, and biomass components, respectively.

The random effects were incorporated into this model to isolate possible biomass differences between administrative districts of Latvia and tree species since the forest type characterizes the species composition and productivity of the forest stand. The variance in random factor or standard deviation of the random variable indicates how much biomass variability is present between individual forest stands across all treatments. According to NFI data, Latvia is divided into 33 districts. Based on forest typology, the forests of Latvia are divided into dry site type forests or forests on wet mineral soils, wet peaty soils, drained mineral soils, or drained peaty soils [29]. A total of 23 forest types in Latvia are distinguished. The species composition index (CI) was calculated as a proportion of the standing volume of species of interest from the standing volume of a stand expressed in tenth parts (numeric).

Stand AGB, BGB, SB, and BB per hectare were fitted using Equation (2):

$$Y_{sc} = a * GS_s^{b_1} + \varepsilon_{sc}, \quad (2)$$

where  $Y_{sc}$  is the observed stand biomass component of the target species (t),  $GS$  is the stand growing stock volume of the target species ( $m^3$ ), and  $a$  and  $b_1$  are parameters. The subscripts  $s$  and  $c$  refer to the stand and biomass components, respectively.

The estimated random effects variances (associated with  $b_1$  parameter in Equation (1) linked with region and forest type were close to 0, indicating that the level of between-group variability was not sufficient to justify the incorporation of these variables into further models. To evaluate how the species composition index influenced the relationships between biomass components and growing stock for each species, this variable was included in Equation (3) as:

$$Y_{sc} = a * GS_s^{b_1} * CI_s^{b_2} + \varepsilon_{sc}, \quad (3)$$

where  $Y_{sc}$  is the observed stand biomass component of the target species (t),  $GS$  is the stand growing stock volume of the target species ( $m^3$ ),  $CI$  is the species composition index, and  $a$ ,  $b_1$ , and  $b_2$  are parameters. The subscripts  $s$  and  $c$  refer to the stand and biomass components, respectively.

We used the standard “nls” function from the stats package in R statistical software to determine the nonlinear (weighted) least squares estimates of the parameters in nonlinear Equations (2) and (3). Among the common goodness-of-fit measures, the root mean square error (RMSE), mean average percent error (MAPE), adjusted coefficient of determination (adj.  $R^2$ ), and residual studies were used to evaluate the accuracy of model estimates. The models were compared on the basis of Akaike’s Information Criterion (AIC). The estimated AIC value indicates the likelihood that a model is correct with a higher penalty for extra parameters in the models [30].

Finally, assessing the performance of Equations (2) and (3) at the national level, the stand-level biomass estimates were compared with the NFI reference data. The results were evaluated by comparing relative differences in relation to the NFI biomass estimates.

### 3. Results

Spearman’s correlation analysis revealed a significant ( $p < 0.001$ ) positive correlation (trend) between AGB, BGB, SB, BB, and all examined forest stand characteristics obtained from the NFI plot-level data (Table 2). Overall, the stand growing stock, followed by the basal area, correlated best with the various stand biomass components, whereas stand age and diameter at breast height were less informative, especially for Scots pine-dominated stands. Among the biomass components, the weakest correlation (0.53–0.96) was found for stand characteristics and the BB, which is the component typically associated with the most biomass variation. Considering the relatively high correlation coefficient (0.82–0.99) with all studied biomass components, the growing stock was included as the only variable to avoid collinearity between predictor parameters in the equations.

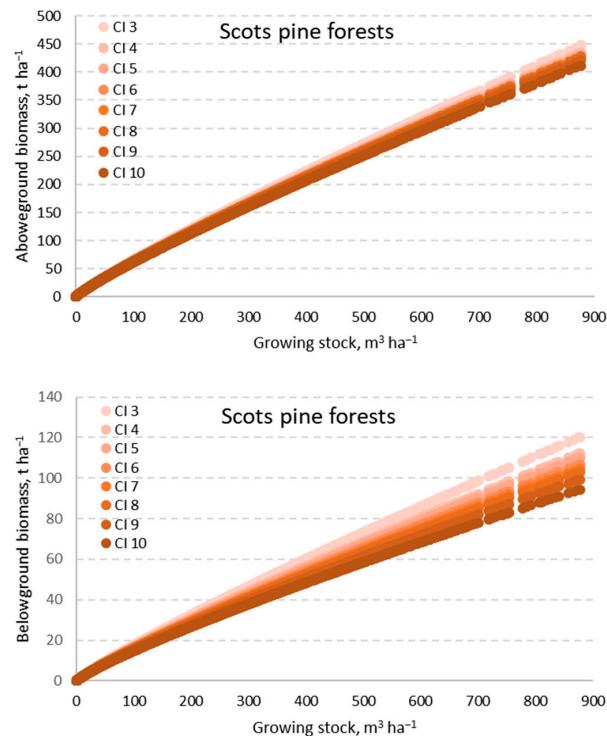
Three random effects (region, forest type, and species composition index) were included in Equation (1) to isolate possible biomass differences. The estimated standard deviation of the random variable (associated with  $b_1$  parameter in Equation (1)) linked with region and forest type in each model was 0, indicating that there was no variability in forest stand biomass across regions and forest types in Latvia. In contrast, the effect of species composition index on the volume–biomass relationship varied according to the biomass components of the different tree species, with BB the component with the greatest influence on the standard deviation of the random variable (Table S1 Supplementary Material).

Figure 1 shows an example of how much variability exists within individual forest stand biomass across all composition index values of the dominant species modeled by Equation (1) for Scots pine forests. There is a close positive relationship between biomass components and stand growing stock for all forest categories, with mixed stands producing the greatest stand biomass for a given growing stock in Scots pine, European aspen, grey

alder, and common alder forests. In birch forests, the opposite was true in that the higher the species composition index (CI) value (pure stands), the greater the stand biomass for a given growing stock.

**Table 2.** Spearman's rank correlation coefficients for species-based forest category total above-ground biomass (AGB), below-ground biomass (BGB), stem biomass (SB), branch biomass (BB), and stand characteristics. All correlations were significant at a level of  $\alpha = 0.001$ .

Forest Category	Variable	Age	Diameter at Breast Height	Height	Basal Area	Growing Stock
Scots pine	AGB	0.56	0.75	0.86	0.94	0.99
	BGB	0.55	0.76	0.86	0.93	0.99
	SB	0.55	0.75	0.89	0.93	0.99
	BB	0.53	0.64	0.62	0.82	0.82
Norway spruce	AGB	0.75	0.77	0.86	0.96	0.99
	BGB	0.75	0.78	0.85	0.96	0.99
	SB	0.79	0.80	0.89	0.94	0.99
	BB	0.62	0.66	0.70	0.92	0.90
Birch	AGB	0.82	0.83	0.91	0.95	0.99
	BGB	0.83	0.85	0.90	0.94	0.99
	SB	0.81	0.82	0.91	0.95	0.99
	BB	0.83	0.84	0.84	0.86	0.93
European aspen	AGB	0.93	0.90	0.94	0.96	0.99
	BGB	0.92	0.90	0.93	0.95	0.99
	SB	0.92	0.89	0.94	0.96	0.99
	BB	0.92	0.91	0.91	0.91	0.96
Grey alder	AGB	0.86	0.85	0.92	0.96	0.99
	BGB	0.83	0.81	0.88	0.97	0.99
	SB	0.86	0.85	0.92	0.97	0.99
	BB	0.86	0.85	0.85	0.88	0.92
Common alder	AGB	0.83	0.78	0.89	0.96	0.99
	BGB	0.79	0.73	0.84	0.96	0.98
	SB	0.82	0.77	0.90	0.96	0.99
	BB	0.77	0.77	0.74	0.81	0.85



**Figure 1.** Above- and below-ground dry biomass variance, when converted to estimates, from random effects in a mixed model (Equation (1)) by composition index (CI) groups and stand growing stock for the Scots pine forest category.

Separate allometric equations were derived for species-based forest categories and stand-level biomass components. The parameter estimates, including the goodness-of-fit statistics of the AGB, BGB, SB, and BB for the basic model (Equation (2)), are shown in Table 3. All parameter estimates were significant ( $p < 0.001$ ) and generally explained between 64% and 99% of the observed stand biomass variability for all forest categories and biomass components. There were no clear trends in model residuals (Figure S1 Supplementary Material) that could reveal systematic discrepancies between the predicted values and the data set.

**Table 3.** The estimated allometric equations and fit statistics for Equation (2).

Forest Category	Component *	Parameter Values $\pm$ Standard Errors		AIC	RMSE	MAPE	adjR <sup>2</sup>		
		a	b <sub>1</sub>						
Scots pine	AGB	1.036	0.016	0.889	0.003	12,837.5	8.2	6.0	0.992
	BGB	0.248	0.006	0.893	0.004	9473.8	3.2	8.0	0.981
	SB	0.375	0.008	1.021	0.003	13,022.5	8.3	9.0	0.989
	BB	1.685	0.111	0.517	0.011	12,837.5	7.9	29.7	0.703
Norway spruce	AGB	1.428	0.031	0.840	0.004	8791.9	8.6	9.48	0.991
	BGB	0.553	0.018	0.782	0.006	6766.5	3.8	17.4	0.976
	SB	0.293	0.006	1.054	0.003	7709.9	5.5	8.4	0.994
	BB	2.895	0.167	0.480	0.010	8505.2	7.6	26.7	0.845
Birch	AGB	0.787	0.011	0.945	0.002	11,816.1	6.4	10.3	0.995
	BGB	0.322	0.009	0.871	0.005	9537.3	3.4	19.9	0.977
	SB	0.522	0.010	0.978	0.003	12,135.7	7.0	10.2	0.990
	BB	0.503	0.038	0.734	0.013	12,283.0	7.3	35.9	0.802
European aspen	AGB	0.644	0.026	0.957	0.006	3850.2	10.3	18.6	0.992
	BGB	0.354	0.023	0.821	0.011	2984.8	4.4	21.8	0.955
	SB	0.489	0.024	0.964	0.008	3823.7	10.0	16.1	0.988
	BB	0.396	0.052	0.758	0.021	3473.3	7.1	39.8	0.878
Grey alder	AGB	0.502	0.020	0.999	0.007	3754.8	6.1	17.0	0.989
	BGB	0.351	0.025	0.816	0.013	2966.3	3.1	15.4	0.971
	SB	0.334	0.010	1.037	0.005	3161.1	3.6	16.8	0.994
	BB	0.299	0.057	0.782	0.035	3769.6	6.1	45.8	0.709
Common alder	AGB	0.701	0.024	0.947	0.006	2663.4	6.9	9.7	0.993
	BGB	0.675	0.050	0.715	0.013	2247.7	4.1	24.0	0.952
	SB	0.322	0.010	1.053	0.005	2411.7	5.0	11.1	0.996
	BB	1.081	0.218	0.543	0.035	2741.8	7.7	58.4	0.643

\* The allometric equation of species-based forest category biomass components:  $Biomass(kg) = a * Growing\ stock^{b_1}$ . Total above-ground biomass (AGB), below-ground biomass (BGB), stem biomass (SB), and branch biomass (BB).

The equations of stand-level dry biomass in six forest categories were tested using one- and two-variable models. In Equation (3), CI and GS were significant predictors for all studied species, improving the basic model in most cases in terms of AIC, RMSE, MAPE, and adjR<sup>2</sup> (Table 4). The elimination of CI only improved the model fit to the data set for two derived biomass functions (the birch BGB component and common alder SB component), resulting in lower AIC scores. The difference between the two AIC values was  $-1$  for both biomass components. In general, the RMSE and MAPE estimates based on Equation (2) were slightly larger than those based on Equation (3), indicating poorer model performance for Equation (2).

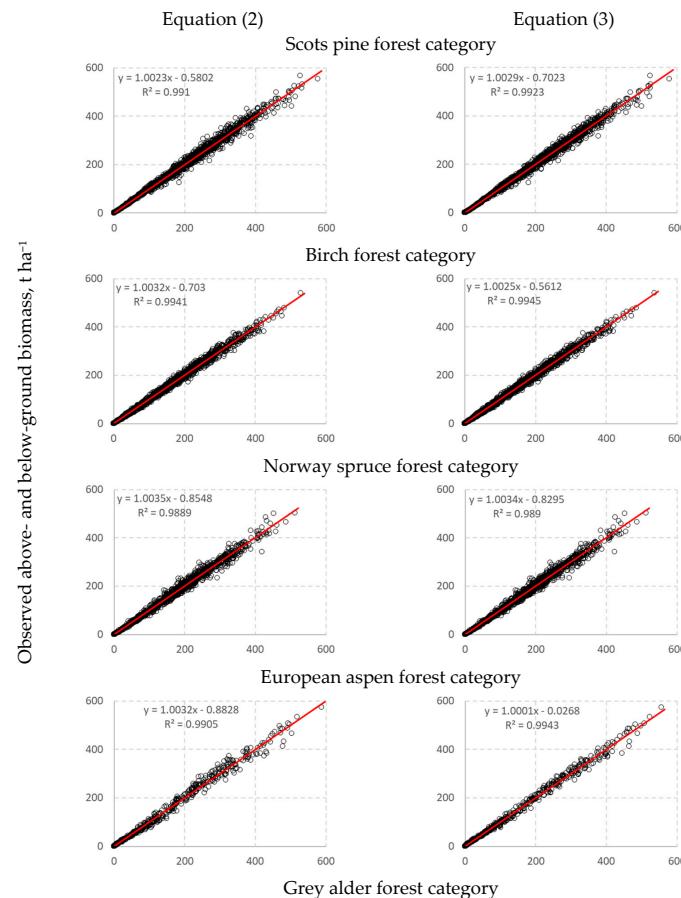
Figure S2 (Supplementary Material) illustrates examples of the variation of the AGB and BGB observed in the NFI plots and their modeled relationship with GS alone (Equation (2)) and GS and CI (Equation (3)) after plot AGB or BGB were estimated using the derived equations for the Scots pine forest category.

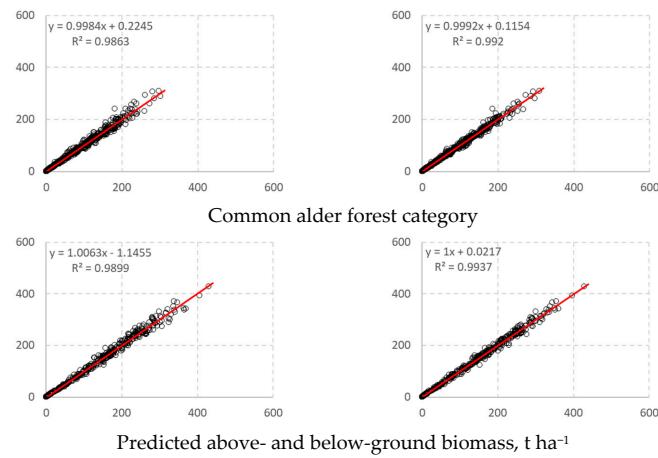
A comparison of Equations (2) and (3) for judging the fit of the model to observed biomass data were analyzed for each biomass component and for the total forest stand biomass, as shown in Figure 2. Statistical tests of intercept ( $a = 0$ ) and slope ( $b = 1$ ) did not detect a significant deviation from the ideal model (1:1 line) for all equations fitted to the dataset.

**Table 4.** The estimated allometric equations and fit statistics for Equation (3).

Forest Category	Component *	Parameter Values ± Standard Errors						AIC	RMSE	MAPE	adjR <sup>2</sup>
		a	b <sub>1</sub>	b <sub>2</sub>							
Scots pine	AGB	1.187	0.022	0.882	0.003	-0.048	0.004	12,802.2	7.9	6.0	0.993
	BGB	0.392	0.009	0.870	0.003	-0.161	0.005	8578.1	2.5	7.0	0.988
	SB	0.344	0.009	1.025	0.003	0.030	0.005	12,986.7	8.3	8.9	0.989
	BB	4.330	0.323	0.477	0.010	-0.352	0.017	12,477.5	7.2	30.1	0.756
Norway spruce	AGB	1.364	0.035	0.841	0.004	0.019	0.006	8783.7	8.5	9.4	0.991
	BGB	0.477	0.019	0.786	0.006	0.062	0.010	6727.1	3.7	17.1	0.977
	SB	0.356	0.008	1.048	0.003	-0.078	0.005	7476.3	5.0	7.8	0.995
	BB	1.583	0.117	0.491	0.009	0.268	0.021	8352.5	7.2	25.1	0.863
Birch	AGB	0.677	0.012	0.956	0.002	0.049	0.004	11,640.5	6.1	10.3	0.995
	BGB	0.314	0.011	0.873	0.005	0.009	0.007	9537.9	3.4	19.7	0.977
	SB	0.339	0.007	1.010	0.003	0.141	0.004	11,147.9	5.3	8.9	0.994
	BB	1.132	0.103	0.679	0.013	-0.276	0.020	12,114.8	7.0	36.9	0.820
European aspen	AGB	0.710	0.025	0.971	0.006	-0.104	0.008	3692.3	8.8	18.2	0.996
	BGB	0.475	0.023	0.848	0.008	-0.261	0.011	2587.5	3.0	19.8	0.987
	SB	0.512	0.025	0.971	0.008	-0.050	0.011	3803.7	9.8	16.2	0.988
	BB	0.634	0.080	0.780	0.020	-0.344	0.029	3351.7	6.3	32.5	0.904
Grey alder	AGB	0.693	0.026	0.986	0.006	-0.131	0.007	3512.9	4.9	16.0	0.994
	BGB	0.641	0.042	0.798	0.010	-0.262	0.015	2718.7	2.5	15.4	0.969
	SB	0.355	0.012	1.035	0.005	-0.025	0.007	3150.1	3.6	16.6	0.994
	BB	1.175	0.223	0.738	0.030	-0.588	0.043	3611.8	5.3	43.2	0.778
Common alder	AGB	0.748	0.021	0.972	0.005	-0.111	0.007	2460.6	5.4	9.7	0.993
	BGB	0.811	0.056	0.746	0.012	-0.194	0.018	2146.4	3.6	16.4	0.965
	SB	0.323	0.010	1.054	0.005	-0.007	0.008	2412.2	5.0	11.3	0.996
	BB	2.226	0.441	0.605	0.034	-0.580	0.050	2639.9	6.7	39.0	0.725

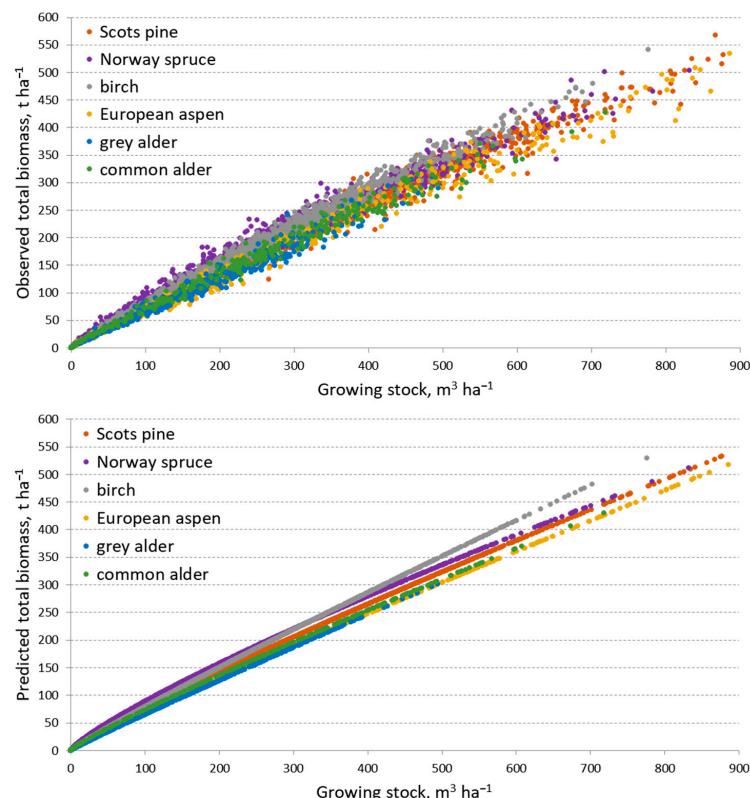
\* The allometric equation of species-based forest category biomass components:  $\text{Biomass(kg)} = a * \text{Growing stock}^{b_1} * \text{Composition index}^{b_2}$ . Total above-ground biomass (AGB), below-ground biomass (BGB), stem biomass (SB), and branch biomass (BB).

**Figure 2.** Cont.



**Figure 2.** The relationship between observed and predicted total (above- and below-ground components) forest stand biomass. The predicted biomass was estimated with Equations (2) and (3) presented in Tables 3 and 4.

The modeling results confirmed that the tendency of the relationship between total stand dry biomass and growing stock was similar in European aspen, grey, and common alder forests and that total biomass was slightly lower than for the other studied forest categories for a given growing stock (Figure 3). In general, if the growing stock was below  $300 \text{ m}^3 \text{ ha}^{-1}$ , the Norway spruce dominant forests had greater total biomass than the other forests. Compared to the other studied forest categories, the total biomass of birch-dominated forests was greater with the increase in the stand growing stock above  $300 \text{ m}^3 \text{ ha}^{-1}$ .



**Figure 3.** The observed and modeled (Equation (2)) relationship between stand level growing stock and total stand biomass (AGB + BGB) in Scots pine, Norway spruce, birch, European aspen, grey alder, and common alder-dominated forests.

Assessing total stand biomass using Equations (2) and (3) instead of currently used individual tree biomass equations [22,23] resulted in small differences in the estimates at the national level of 0.17% and 0.14%, respectively (Table S2 Supplementary Material). At the level of studied forest categories, the differences seem acceptable and smaller for Equation (3) (0.01–0.21%) than Equation (2) (0.09–0.32%). These results indicate that Equations (2) and (3) can be used to transform growing stock volume data into national biomass estimates by forest category.

#### 4. Discussion

At the national level, NFI data are the most practical means of modeling forest stand biomass and estimating carbon stocks, as forest data are usually collected from all populations of interest in a statistically sound and verified manner. The elaboration of models was intended to contribute to the knowledge of the relationship between stand growing stock, a variable often measured in forestry, and the forest stand biomass of different components. Our study meets a need to improve forest stand biomass predictions by making it possible to calculate the species composition index according to stand growing stock data of different forest categories. This study was limited to NFI sample plots established in Latvia on forest land according to the FAO definition [31].

Frequently, total forest stand or above- and below-ground biomass components are estimated using easily measurable stand characteristics obtained via NFI plot-level data or field investigations [3,10,11,16]. We observed a strong and significant relationship between studied stand components (AGB, BGB, SB, and BB) and stand characteristics (stand age, DBH, H, G, and GS). Based on Spearman's rank correlation coefficients linking forest stand variables and biomass of a particular stand component (Table 2), the biomass of every forest category was estimated more or less accurately using these stand variables in allometric equations. However, among the studied stand variables, the closest correlation, especially for stand AGB and BGB portions, was found with growing stock. It is not surprising that the growing stock volume is the most commonly used variable converted into estimates of above- and below-ground woody biomass, as the volume of growing stock is reported as one of the most important forest characteristics monitored by NFIs to quantify wood resources [8]. Methods to estimate growing stock differ by country, with growing stock definitions and calculation methods differing due to country-specific conditions, justifying the need for national stand-level equations.

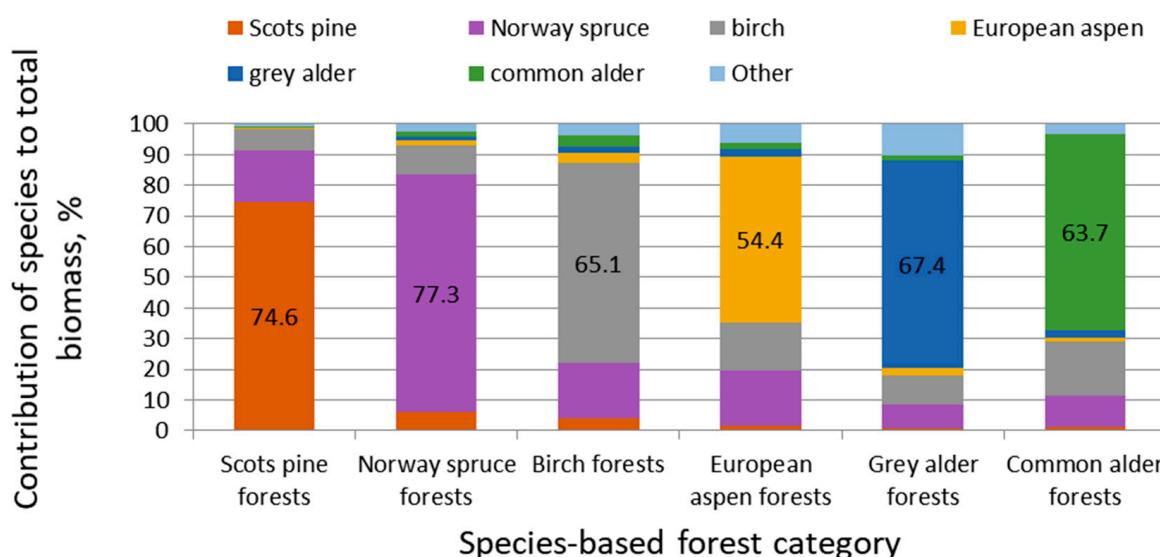
The mean growing stock, according to the Latvian NFI data (from 2016 to 2020), was  $210.4 \text{ m}^3 \text{ ha}^{-1}$ , varying by forest category from  $123.6 \text{ m}^3 \text{ ha}^{-1}$  in gray alder forests to  $265.8 \text{ m}^3 \text{ ha}^{-1}$  in Scots pine forests (Table 1). Similarly, the forest stand biomass density (AGB + BGB) differed among forest categories, where the estimated stand biomass in grey alder forests ( $78.2 \text{ t ha}^{-1}$ ) was more than two times less than in Scots pine forests ( $178.9 \text{ t ha}^{-1}$ ). The stand biomass density per unit of forest area in Latvia was approximately  $147.9 \text{ t ha}^{-1}$  (AGB  $117.2 \text{ t ha}^{-1}$  and BGB  $30.7 \text{ t ha}^{-1}$ ), which was more, on average, than in boreal forests but less than in temperate forests [6,32].

In this study, stand growing stock alone and in combination with species composition index as variables were examined in Equations (2) and (3), respectively, to calculate the stand biomass of different components. AGB, BGB, SB, and BB by forest category were better estimated using Equation (3) than the simplest model (Equation (2)). The values of all the model parameters were biologically consistent. Although the simpler model met the requirements of heteroscedastic model residuals (Figure S1 Supplementary Material) and fitted the observed data well (Figure 2), its accuracy in terms of RMSE, MAPE, and adjR<sup>2</sup> was lower compared to the model including species composition index as a variable. Equation (2) had a higher probability of being a superior function only for the prediction of the birch BGB component and common alder SB component, resulting in lower AIC scores than Equation (3). The difference between the two AIC values was  $-1$  for both biomass components. According to Motulsky and Arthur [30], with such a small difference between

two AIC scores, we cannot be sure that the best model is more appropriate; the data are simply ambiguous.

The biomass stock of the six studied forest categories accounted for 97.8% of the total forest biomass in Latvia, indicating that the study material represents the bulk of all Latvian forests. More than half (55%) of the biomass stock was accumulated in coniferous forests, and the Scots pine forests alone, as the dominant forest category, contributed 34.1% to the total biomass stock. The majority of the forest biomass stock in Latvia can be characterized by a few tree species, in contrast to temperate forests, where there is a slightly higher tree species diversity [24,25].

The forest category and composition of the dominant species have an impact on stand biomass density, indicating that forests with similar growing stock can have different structures and component biomass. The dominant species in each forest category were the essential contributors to the accumulation of forest stand biomass (Figure 4). Compared to birch, aspen, and alder forests that were heterogeneous with mixed species biomass, coniferous forests were more homogeneous in terms of species composition. The contributions of the dominant species to total biomass for pine and spruce forests were 74.6% and 77.3%, respectively, while in the range of 54.4% to 67.4% in deciduous forests. The greater the admixture proportion of other species, the greater the differences in biomass density are expected at the same growing stock.



**Figure 4.** Contribution of tree species to the total forest stand biomass for main species-based forest categories in Latvia.

Numerous studies have revealed differences in stand-level biomass allocation patterns [19,33,34]. The contribution of the various biomass components (branches, stems, and roots) to the total biomass depends on the forest category and stand age, but most studies indicate that the largest part of the total tree or stand biomass corresponds to stems. From the studied species, the birch has the highest stem wood basic density, while density for coniferous species—Scots pine and Norway spruce—and deciduous species—aspen, grey alder, and common alder—is lower [35–37], indicating that birch stem biomass will be greater at the same stem volume. Therefore, the admixture of birch in stands dominated by other tree species enhances total biomass yield at a given growing stock. The admixture of Norway spruce in forest stands (Figure 4) also increases total biomass yield, mainly due to the biomass of the branches [19,38,39], the share of which is higher in the total biomass of spruce than in other studied species (negative  $b_2$  parameter in Table 4).

In this study, we did not aim to improve the Latvian NFI to report biomass and C stocks, but rather, we intended to present a methodology for calculating stand-level biomass components in cases where individual tree measurements are not available. Applying our

models (Equations (2) and (3)), it is possible to calculate the biomass and carbon stocks [40] for forest categories according to the dominant species common in Latvia and hemiboreal forests. We found that forests with the same growing stock can have different amounts of biomass due to their dominant and admixture species. Overall, both Equations (2) and (3) are appropriate for estimating stand biomass components for all studied forest categories. However, unless information on species-specific growing stock is available, we recommend using Equation (3) with stand growing stock and composition index according to dominant species as variables. The elaborated models can be used for calculating the national scale biomass of forest categories and carbon stocks in Latvia regardless of the region and forest type.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/land11071108/s1>; Table S1: the estimated allometric equations incorporating species composition index as random effect and fitting statistics for Equation (1); Figure S1: an example of how Pearson residuals are analyzed for the Equations (2) and (3) by RMSE for above- and below-ground biomass components of Scots pine forests category; Figure S2: an example of the relationship between stand level growing stock and above- and below-ground dry biomass (AGB and BGB, respectively) for the Scots pine forest category. The predicted values were estimated with the AGB and BGB functions presented in Tables 3 and 4; Table S2: National level forest stand biomass (AGB + BGB) estimated by the NFI (reference) and Equations (2) and (3). The difference, %, is expressed as the absolute percent difference between the NFI reference value and the estimates obtained from equations presented in Tables 3 and 4.

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