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Comparing of allometric models of single-tree biomass intended for airborne laser sensing and terrestrial taxation of carbon pool in the forests of Eurasia

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Abstract

For the main tree species in North America, Europe, and Japan, a number of thousands of allometric equations for single-tree biomass estimation using mostly tree height and stem diameter at breast height are designed. An innovative airborne laser method of the forest canopy sensing allows to process online a number of morphological indices of trees, to combine them with the biomass allometric models, and to evaluate the forest carbon pools. The database of 28 wood and shrub species containing 2.4 thousand of definitions is compiled for the first time in the forests of Eurasia, and on its basis the allometric transcontinental models of fractional structure of biomass of two types and dual use are developed. The first of them include as regressors the tree height and crown diameter and are intended for airborne laser location, whereas the latter have a traditional appointment for terrestrial forest biomass taxation using tree height and stem diameter. It is found that the explanatory capacity of the first model in comparison with the second one for foliage, branches, and roots is lower, but this difference is not statistically significant. The same capacity for the stem and aboveground biomass is lower too but this difference is statistically significant. Both models are designed for two different methods of taxation and cannot replace one another.

Summary for Managers

- We develop an innovative airborne laser method of the forest canopy sensing to evaluate the forest carbon pools.
- We show this approach is highly reliable: in the most cases, there is more than 90% of tree biomass variability.
- Processing speed of laser location, incommensurable with the terrestrial mensuration, gives the possibility to assess the change of carbon pool of forests on some territory during its periodic overflights.
- The proposed information can be useful when implementing activities on climate stabilization, as well as in the validation of the simulation results when evaluating the carbon depositing capacity of forests.

1 | INTRODUCTION

At the climate summit in Paris in 2015 December, 196 countries pledged to reduce carbon emissions and prevent rising average temperatures more than 2°C by the end of the century. The important role in this relation is belonging to forest ecosystems, as sinks for atmospheric carbon. In this regard, the technologies evaluating the carbon-depositing function of forest cover are actively improved, and a number of its empirical and simulation models are developed having in mind joint using the ground forest inventory data and the methods of remote sensing (Lezhnin, Nezamaev, Novokshonova, & KOmarova, 2010; Zheng, Heath, & Ducey, 2007).

Laser sensing (location) the forest canopy is today an component part of the latest techniques and technologies in digital photogrammetry and GIS and in many respects it is superior to not only other remote sensing methods of measurement and study of forest canopy (Danilin, 2003; Lim & Treitz, 2004; Maltamo, Eerikäinen, Pitkänen, Hyyppä, & Vehmas, 2004; Stone, Penman, & Turner, 2012), but also the methods of terrestrial taxation (Næsset, 2002; Næsset et al., 2004). In recent years, a fundamental new laser-shooting method of forest canopy measurement, that enables us to handle the massive amounts of data (hundreds of gigabytes) of laser sensing in real time, almost simultaneously with the execution of the measurements, not just of the nameless forest cover but also of individual trees (Danilin, 2003; Danilin, Medvedev, & Melnikov, 2005).

Because trees of different species have specific configuration of vertical profile, this specificity is recognized today by using airborne laser (lidar) technology. When multiple registration with lidar of reflected pulses the method is able to distinguish pine, spruce, and small-leaved species with an accuracy of 95% using the density of point clouds and the outline of tree profile. Pine differs from birch

with typical points of local crown density and spruce differs from other species with its crown shape (Holmgren, Persson, 2004; Næsset et al., 2004).

Even in the 1960–1970 years, the methods of aerial techniques allow to define the parameters such as tree height, crown diameter, and projection area with greater precision than with ground works (Sinitsyn & Sukhikh, 1979; Weaver, 1977). In open forest communities of desert zone of Central Asia, submitted by *Haloxylon* Bunge communities, the crown diameter has a diagnostic function, inherent to stem diameter at breast height in the forest zone, that gave us an opportunity to develop regression models to estimate their biomass upon total height and crown diameter used as in terrestrial taxation and in air photography (Usoltsev, 1988; Veyisov & Kaplin, 1976). Until recently, such an approach to the evaluation of tree biomass in the forest zone was not used due to the high horizontal and vertical canopy density. Modern laser-shooting method allows us to record not only visible, but "hidden" under the upper canopy trees. These advantages of remote sensing method are repeatedly amplified due to the data processing rate, provided by the above-mentioned laser-shooting method.

For a global quantitative description of biosphere functions of forest cover, the relevant databases are required, which involve the biological production characteristics of the world's forests. Such database are actively formed today, in connection with that the scientific community established the entry into the Big Data Era (https://www.gfbinitiative.org/symposium2017). When using the compiled "big data," the global patterns on biological productivity of forest ecosystems and their constituent trees are designed (Crowther et al., 2015; Jucker et al., 2017; Liang et al., 2016; Poorter et al., 2015).

The purpose of this study is to develop allometric models to estimate component structure of tree biomass of the main tree and some bush species of Eurasia having the aim of laser-shooting evaluation of forest biomass and atmospheric carbon deposition.

2 | METHODS AND DATA

To implement this goal, we formed the database on tree biomass and taxation indices by literary sources, using the materials of sample plots established on the territory from Britain to China and Japan (Table 1). About 87% of data are taken from Russian-language literature of the former Soviet Union.

The main taxation indices measuring the tree biomass and included in the compiled database are the age, stem diameter and tree height, crown length and crown diameter, as well as stand density of the plot where the tree biomass was measured. In addition, the stem volume and the coordinates of the plots are shown, which is necessary for geographical analysis of tree biomass data.

The authors of publications whose data brought in the compiled database are cited too. The database structure is shown as its fragment (Table 2). Its two variants are available online at: https://elar.usfeu.ru/handle/123456789/4931 and https://elar.usfeu.ru/handle/123456789/6103.

Methods of estimating tree biomass on the sample plots used by different researchers are differed insignificantly, which cannot be said about root biomass that were defined by archaeological (Le Goff & Ottorini, 2017), explosive (Whittaker & Woodwell, 1968), multiple-stage (Snowdon et al., 2002), electrometric (Yakushev, 1972), and sometimes indirect (Snowdon, 1992) methods. Methods for determination of tree biomass at the sites shown in the Table 2, were presented in previous publications (Usoltsev, 1990; Usoltsev & Krepkii, 1994).

Today we have about 2600, 800, and 1000 allometric equations for estimating tree biomass, using mostly tree height and diameter at breast height for the main tree species in North America, Europe, and Japan, respectively (Hosoda & Iehara, 2010; Jenkins, Chojnacky, Heath, & Birdsey, 2004; Muukkonen & Mäkipää, 2006). All of them are intended for terrestrial forest taxation only.

TABLE 1 Distribution of the single tree number having measurements of tree biomass (kg) by species and countries

Genus (subgenus, species)	Latin name	Country	Single tree number[a]
Pine	Subgenus *Pinus* L.	Russia, Kazakhstan, United Kingdom, Czech Republic, Bulgaria, China, Japan, Switzerland, Belarus, Slovakia, Latvia, Iraq	2684/1006
Spruce	*Picea* A. Dietr.	Russia, Germany, Czech Republic, Bulgaria, Switzerland, Latvia, Belgium, Sweden, Italy	977/478
Fir	*Abies* Mill.	Russia, Czech Republic, Japan	173/96
Larch	*Larix* Mill.	Russia, Japan, China, Czech Republic, Switzerland, Kazakhstan, Mongolia	522/139
Siberian pine	Subgenus *Haploxylon* (*Koehne*) Pilg.	Russia	170/93
Cryptomeria	*Cryptomeria* D.Don	Japan	29/29
Chamaecyparis	*Chamaecyparis* Spach	Japan	10/10
Pseudotsuga	*Pseudotsuga* Carr.	Belgium, Bulgaria	13/6
Birch	*Betula* L.	Russia, Kazakhstan, Mongolia, Japan, China, United Kingdom, France, Belgium, Finland, Azerbaijan	1277/170
Aspen and poplar	*Populus* L.	Russia, Kazakhstan, Mongolia	513/39
Linden	*Tilia* L.	Russia, Czech Republic, Bulgaria	402/138
Alder	*Alnus* Mill.	Russia	24/16
Oak	*Quercus* L.	Russia, Bulgaria, Japan, Czech Republic, Switzerland, Hungary	130/18
Beech	*Fagus* L.	France, Germany, Czech Republic, Italy, Sweden, Denmark	56/33
Ash	*Fraxinus* L.	Russia, Czech Republic, China	31/13
Hornbeam	*Carpinus* Decne	Bulgaria, Russia	22/7
Robinia pseudoacacia	*Robinia pseudoacacia* L.	Slovakia, Bulgaria	24/18
Willow	*Salix* L.	Russia, Sweden	23/10
Maple	*Acer* L.	Russia, Bulgaria	27/14
Elm	*Ulmus* L.	Russia	9/7
Chosenia	*Chosenia* Nakai	Russia	17/8
Hawthorn	*Crataegus* L.	Russia	8/6
Prunus sylvestris	*Prunus padus* L.	Russia	8/6
Juglans mandshurica	*Juglans mandshurica* Maxim.	Russia	7/7
Maackia	*Maackia amurensis* Rupr.	Russia	7/7
Phellodendron amurense	*Phellodendron amurense* Rupr.	Russia	7/7
		Total	7265/2381

[a]The first number is the total tree quantity, the second is the number of trees with the measured crown diameter.

TABLE 2 The database fragment of biomass of trees growing on the territory of Eurasia (Usoltsev, 2016a, b)

No.	A (years)	D (cm)	H (m)	L_{cr} (m)	D_{cr} (m)	Stem volume (dm^3)		Dry biomass (kg)						N
						V_t	V_b	P_s	P_b	P_{br}	P_f	P_a	P_r	
Turgay deflection, Aman–Karagay island-like forest; steppe zone; natural forests *Pinus sylvestris* L. 52°20′ N, 64°00′ E														
890	20	3.07	3.00	1.61	0.90	1.54	0.568	0.646	0.173	0.151	0.371	1.17	0.82	82400
891	20	2.35	3.11	1.74	0.61	1.15	0.457	0.395	0.104	0.073	0.054	0.522	0.59	
892	20	3.15	2.75	2.61	0.86	1.81	0.532	0.695	0.167	0.154	0.157	1.01	0.95	
928	22	4.96	5.81	3.56	1.29	6.93	2.165	2.350	0.590	0.181	0.425	2.96	1.279	43810
929	22	5.02	6.72	3.40	1.00	7.03	1.439	2.660	0.520	0.137	0.415	3.21	1.189	
930	22	3.03	6.20	3.12	1.09	3.17	0.797	1.358	0.298	0.072	0.167	1.60	0.536	
931	22	2.59	5.72	3.32	0.585	2.35	0.644	0.930	0.246	0.041:	0.103	1.07:	0.525	
932	22	2.07	4.31	2.55	0.59	1.13	0.353	0.468	0.126	0.0292	0.063	0.56	0.198	
987	42	8.00	12.0	4.08	1.21	29.7	5.815	12.71	1.71	0.370	0.570	13.65	7.80	19136
988	42	7.57	10.9	4.41	1.26	26.4	5.394	10.18	1.68	0.350	0.470	10.94	3.90	
989	42	5.51	10.5	2.64	0.84	14.3	3.249	6.00	1.02	0.120	0.180	6.31	1.882	
992	42	2.98	6.42	2.72	1.04	3.11	0.677	1.36	0.28	0.109	0.070	1.56	0.283	
993	42	2.35	5.69	0.91	0.77	1.33	0.409	0.57	0.14	0.060	0.020	0.65	0.113	
994	42	2.03	4.28	1.35	0.65	0.945	0.289	0.428	0.088	0.039	0.023	0.49	0.170	
Magadan region, Yana river; northern taiga zone; forests *Larix cajanderi* Mayr. 60°30′ N, 148°00′ E														
298	202	52.8	30.0	21.4	8.95	2496.7	312.2	1204.0	167.0	117.5	16.07	1337.6	551.9	504
299	168	46.5	26.6	18.3	9.35	1936.0	243.9	929.0	133.0	142.1	23.43	1094.5	476.4	
300	125	34.8	27.5	14.5	5.75	1196.2	154.0	576.0	72.0	50.10	11.12	637.2	203.2	
301	116	26.0	23.6	16.6	5.15	764.0	107.7	318.3	50.3	47.80	12.30	378.4	180.4	
302	120	25.3	22.4	14.4	6.00	605.6	14.0	286.6	38.6	36.70	6.61	329.9	149.9	
307	225	36.0	25.5	12.6	6.55	1214.3	100.1	593.72	46.76	41.06	6.40	641.2	325.1	627
308	202	24.0	21.4	6.7	5.95	385.6	27.0	188.65	12.61	40.40	6.10	235.1	79.02	

(Continued)

TABLE 2 The database fragment of biomass of trees growing on the territory of Eurasia (Usoltsev, 2016a, b)

| No. | A (years) | D (cm) | H (m) | L_{cr} (m) | D_{cr} (m) | Stem volume (dm³) | | Dry biomass (kg) | | | | | | | |
						V_t	V_b	P_s	P_b	P_{br}	P_f	P_a	P_r	N
314	193	23.3	17.6	10.2	4.15	385.2	29.8	188.42	13.92	11.39	2.79	202.6	108.9	860
315	198	18.3	15.6	5.9	3.75	206.1	13.2	100.89	6.19	6.05	1.04	108.0	59.25	
319	400	25.2	13.7	9.8	4.75	291.6	31.2	142.39	14.99	20.01	6.15	168.5	69.93	394
320	230	20.0	15.2	7.0	3.95	232.9	38.0	113.43	17.75	7.91	1.74	123.1	51.02	
321	205	14.0	9.5	7.25	4.25	69.6	8.9	33.96	4.16	7.60	1.50	43.06	33.43	

Designations in the Table 2: A, tree age, years; D, DBH, cm: M, tree height, m; L_{cr}, crown length, m; D_{cr}, crown diameter, m; V_t, stem volume with bark, dm³; V_b, stem bark, dm³; P_{st}, stem biomass with bark, kg; P_b, stem bark biomass, kg; P_{br}, branch biomass, kg; P_f, foliage biomass, kg; P_a, aboveground biomass, kg; P_r, root biomass, kg; N, tree number per ha.

The database compiled gives an opportunity to develop for each species the transcontinental allometric models of component biomass structure, including crown diameter and tree height as regressors:

$$\ln P_{\mathrm{i}} = a_0 + a_1 \ln H + a_2 \ln D_{\mathrm{cr}} \tag{1}$$

and compare their explanatory ability with traditional allometric model

$$\ln P_{\mathrm{i}} = a_0 + a_1 \ln H + a_2 \ln \mathrm{DBH}, \tag{2}$$

where P_{i} is dry biomass of stem above bark, branches, foliage, aboveground part, and roots (P_{st}, P_{br}, P_{f}, P_{a}, and P_{r}, respectively; kg); H is tree height (m); D_{cr} is the crown diameter (m); DBH is diameter at breast height (cm).

Unfortunately, when processing model trees on the plot, researchers usually measured their age, height, and DBH, because their combination explained 90–99% of the variability of one or another biomass component. Sometimes the crown length also measured, but rarely is its diameter. It was believed that the latter morphometric index makes no significant contribution to the explanation of the variability of tree biomass, which was provided by the above-mentioned indices. In addition, due to the irregular shape of the crown horizontal projection, the accuracy of its diameter measurement was questionable, anyway, much lower than the accuracy of DBH measurement.

That is why during calculation models: (1) we were forced to use only a portion of the compiled database, namely only those trees that had measured the crown diameter. Their share in the total amount of data amounted to 33% (Table 1). To ensure the comparability of the explanatory capacity of models (1) and (2), the calculation of (2) is made on the same tree quantity as the model (1). Calculation of compared allometric biomass models is made by means of the least squares method with dependence linearity by means of log transformation and with the introduction of correction factor related to retransformation by Baskerville (1972).

3 | RESULTS AND DISCUSSION

The results of sequential calculation of equations (1) and (2) are summarized in Table 3. When calculating equation (1), the index of stand density was statistically not significant in the most cases because it correlates with both the crown diameter, and with a stem diameter. Because coniferous and small-leaved species have some differences in their crown profiles, our analysis of adjR^2 and SE, characterizing the equations (1) and (2) for biomass components P_i, and estimating their differences in relation to the mentioned equations is fulfilled separately (Table 4).

The results of comparative analysis showed that the explanatory capacity of equation (1) in comparison with equation (2) for foliage, branches, and roots are somewhat lower, but this difference is not statistically significant. Error SE of equations for the same components are shown earlier, but this difference is not statistically significant too. Explanatory ability of equation (1) in comparison to equation (2) for stem biomass and aboveground one is also lower on average 4.6%, but this difference is statistically significant: t_{akt} is 3.4 and 3.6, respectively, which is higher than the standard values. But models (1) and (2) are designed for two different methods of taxation and cannot replace one another.

According to the study by Semechkina (1978), the variability of the biomass of pine needles and branches (110% and 115% correspondingly) are significantly higher when compared with the variability of stem biomass (86%). At the same tree height the ability to explain the variability of the masses of foliage and branches by means of stem diameter value is higher than by the value of the width of the

TABLE 3 Characteristics of equations (1) and (2)

Genus (subgenus, species)	Biomass component	Coefficients of equations (1)			Coefficients of equations (2)			adjR² for equations[a]		SE for equations[a]	
		a_0	a_1	a_2	a_0	a_1	a_2	(1)	(2)	(1)	(2)
Pine	P_{st}	−3.1393	2.3927	0.7586	−3.5394	1.1437	1.6275	0.976	0.988	0.47	0.32
	P_{br}	−3.2663	1.3197	1.7788	−4.6377	−0.4181	2.8385	0.940	0.938	0.75	0.76
	P_f	−2.3392	0.8007	1.7480	−3.7731	−0.7283	2.6522	0.905	0.897	0.81	0.84
	P_a	−2.2266	2.0420	1.0193	−2.9648	0.7693	1.8662	0.968	0.981	0.52	0.41
	P_r	−3.7068	1.9909	0.9533	−4.6976	0.8402	1.9803	0.951	0.943	0.64	0.69
Spruce	P_{st}	−2.8011	2.4371	0.2117	−2.8844	1.6827	0.9098	0.969	0.973	0.43	0.41
	P_{br}	−2.4490	1.4247	1.0440	−2.0099	−0.3511	1.9517	0.862	0.825	0.63	0.71
	P_f	−2.0075	1.3577	0.6348	−1.9497	−0.3483	1.8758	0.766	0.868	0.74	0.57
	P_a	−1.6619	2.0590	0.4763	−1.5354	0.7692	1.4307	0.933	0.956	0.49	0.42
	P_r	−2.9172	1.7245	1.0962	−2.8387	0.5039	1.6769	0.916	0.933	0.61	0.59
Fir	P_{st}	−2.8081	2.3994	0.6382	−3.3777	1.5062	1.2679	0.967	0.988	0.31	0.28
	P_{br}	−2.7805	1.4644	1.3322	−4.0986	1.1858	1.2713	0.920	0.927	0.43	0.63
	P_f	−2.5619	1.4499	0.9190	−3.5097	0.3844	1.6969	0.882	0.928	0.46	0.53
	P_a	−1.8772	2.1239	0.7442	−2.5107	1.2327	1.3340	0.957	0.982	0.33	0.32
	P_r	−1.6498	0.6790	2.3737	−1.3831	−0.3906	2.0049	0.628	0.849	0.72	0.66
Larch	P_{st}	−3.5824	2.5903	0.8256	−3.2995	1.3845	1.3905	0.969	0.987	0.38	0.24
	P_{br}	−2.9393	1.1133	1.9212	−3.0477	−0.1917	2.1326	0.931	0.909	0.51	0.59
	P_f	−3.1799	0.7475	1.7233	−3.2759	−0.4339	1.9208	0.874	0.851	0.58	0.64
	P_a	−2.7821	2.2658	1.0182	−2.5752	1.0407	1.5224	0.969	0.986	0.36	0.24
	P_r	−0.3436	0.5916	1.8637	−1.3825	−0.8031	2.5524	0.692	0.713	0.69	0.67
Siberian pine	P_{st}	−2.4756	1.9903	1.1096	−3.2206	0.9483	1.6857	0.957	0.977	0.40	0.30

(Continued)

TABLE 3 Characteristics of equations (1) and (2)

Genus (subgenus, species)	Biomass component	Coefficients of equations (1)			Coefficients of equations (2)			adjR² for equations[a]		SE for equations[a]	
		a_0	a_1	a_2	a_0	a_1	a_2	(1)	(2)	(1)	(2)
	P_{br}	−2.3906	1.1642	1.7494	−3.5024	−0.1458	2.3366	0.878	0.904	0.62	0.55
	P_f	−1.7534	0.5159	1.9816	−3.0159	−0.9572	2.6364	0.845	0.892	0.58	0.49
	P_a	−1.3566	1.6119	1.3220	−2.2313	0.4535	1.9284	0.944	0.970	0.43	0.31
	P_r	–	–	–	–	–	–	–	–	–	–
Cryptomeria	P_{st}	−2.8439	2.2423	1.1368	−3.6153	1.3787	1.4366	0.983	0.983	0.14	0.14
	P_{br}	−3.3204	0.9538	2.5647	−4.9741	−0.7818	3.0229	0.941	0.902	0.24	0.31
	P_f	−0.7444	0.5665	1.8165	−2.0648	−1.0398	2.5276	0.876	0.943	0.24	0.16
	P_a	−1.6556	1.7995	1.3790	−2.5783	0.7874	1.7063	0.982	0.978	0.13	0.14
	P_r	−2.6007	1.6386	1.5098	−3.6408	0.4502	1.9504	0.971	0.976	0.16	0.15
Chamaecyparis	P_{st}	−1.7386	2.0776	0.4186	−3.5754	0.6996	2.1071	0.908	0.993	0.31	0.09
	P_{br}	−0.7631	0.5023	1.4036	−4.2696	−1.3786	3.5915	0.694	0.964	0.42	0.15
	P_f	−0.0332	0.7522	0.1031	−1.6122	−0.7460	1.9883	0.425	0.844	0.34	0.19
	P_a	−0.3952	1.5907	0.5523	−2.4985	0.1055	2.3579	0.853	0.990	0.33	0.08
	P_r	−1.3175	1.5122	0.5027	−3.4982	−0.1076	2.4860	0.813	0.987	0.36	0.10
Pseudotsuga	P_{st}	−13.179	5.6405	−0.0777	−7.0991	3.0918	0.7693	0.929	0.981	0.13	0.07
	P_{br}	−25.876	8.0538	0.4335	−19.5417	5.0765	1.4082	0.770	0.816	0.43	0.39
	P_f	−14.1366	4.6197	0.2943	−8.0874	1.8516	1.2036	0.547	0.634	0.38	0.35
	P_a	−13.4559	5.7169	−0.0431	−7.3785	3.1478	0.8097	0.926	0.980	0.14	0.07
	P_r	–	–	–	–	–	–	–	–	–	–

(Continued)

TABLE 3 Characteristics of equations (1) and (2)

Genus (subgenus, species)	Biomass component	Coefficients of equations (1)			Coefficients of equations (2)			adjR² for equations[a]		SE for equations[a]	
		a_0	a_1	a_2	a_0	a_1	a_2	(1)	(2)	(1)	(2)
Birch	P_{st}	−4.7194	2.9127	0.6253	−3.4471	1.1568	1.6545	0.955	0.986	0.41	0.23
	P_{br}	−5.5005	2.2617	1.2545	−3.9871	−0.2623	2.6566	0.875	0.937	0.73	0.51
	P_f	−4.7588	1.5025	1.1359	−3.6690	−0.3629	2.0858	0.849	0.900	0.61	0.49
	P_a	−4.3708	2.7961	0.7577	−3.0518	0.8755	1.8703	0.942	0.980	0.47	0.27
	P_r	−3.5001	2.3956	0.2353	−3.3208	0.3981	2.0299	0.642	0.976	0.67	0.15
Aspen and poplar	P_{st}	−3.9623	2.0536	1.6066	−3.7682	1.0645	1.7992	0.935	0.991	0.30	0.12
	P_{br}	−3.5760	0.4156	3.1638	−2.8625	−1.6573	3.5480	0.838	0.939	0.60	0.37
	P_f	−3.7598	0.2241	2.6885	−3.2036	−1.6842	3.1602	0.780	0.965	0.60	0.24
	P_a	−3.4758	1.8460	1.7906	−3.1762	0.7054	2.0151	0.922	0.987	0.34	0.14
	P_r	−	−	−	−	−	−	−	−	−	−
Linden	P_{st}	−4.7783	3.1643	0.3170	−4.2180	1.2493	1.7973	0.888	0.989	0.44	0.14
	P_{br}	−3.4913	1.9167	0.6814	−2.9962	−0.8215	2.7557	0.655	0.883	0.72	0.42
	P_f	−4.0664	1.4374	0.6879	−3.9833	−0.3150	1.9702	0.594	0.678	0.69	0.62
	P_a	−3.9391	2.9120	0.3724	−3.4063	0.9134	1.9099	0.865	0.983	0.46	0.16
	P_r	−	−	−	−	−	−	−	−	−	−
Alder	P_{st}	−5.2391	2.5164	1.3219	−3.6378	0.7795	1.9666	0.958	0.996	0.24	0.07
	P_{br}	−7.3392	1.4468	3.2791	−4.3498	−1.4914	3.8172	0.909	0.917	0.42	0.40
	P_f	−7.3349	1.3924	2.4827	−5.1102	−0.7736	2.8447	0.895	0.895	0.37	0.37
	P_a	−5.0649	2.3968	1.5236	−3.3137	0.5227	2.1676	0.954	0.994	0.25	0.09
	P_r	−	−	−	−	−	−	−	−	−	−

(Continued)

TABLE 3 Characteristics of equations (1) and (2)

Genus (subgenus, species)	Biomass component	Coefficients of equations (1)			Coefficients of equations (2)			adjR² for equations[a]		SE for equations[a]	
		a_0	a_1	a_2	a_0	a_1	a_2	(1)	(2)	(1)	(2)
Oak	P_{st}	−4.8524	2.9380	0.9356	−3.5687	1.2025	1.7416	0.981	0.995	0.27	0.14
	P_{br}	−5.1712	1.6865	2.4446	−2.2683	−2.2777	4.1539	0.922	0.953	0.62	0.49
	P_f	−4.2509	0.9144	1.8570	−2.0610	−2.0512	3.1237	0.890	0.921	0.51	0.43
	P_a	−3.4632	2.2244	1.5306	−1.7935	−0.0097	2.4285	0.910	0.910	0.60	0.60
	P_r	−	−	−	−	−	−	−	−	−	−
Beech	P_{st}	−7.0035	3.6349	0.9830	−3.4592	0.9143	2.0178	0.980	0.998	0.28	0.09
	P_{br}	−8.2275	2.9395	1.9533	−4.0757	−0.4831	3.0181	0.945	0.952	0.53	0.50
	P_f	−5.9158	1.7314	1.4092	−0.2960	−2.5603	3.0884	0.883	0.961	0.52	0.30
	P_a	−6.5782	3.4798	1.1162	−2.8682	0.6046	2.1842	0.979	0.998	0.28	0.08
	P_r	−9.3817	4.0811	0.5825	−2.3777	−0.8150	2.8319	0.856	0.985	0.45	0.15
Ash	P_{st}	−5.4356	3.2511	0.6154	−3.3936	0.9774	1.8969	0.941	0.992	0.37	0.14
	P_{br}	−8.6651	3.3211	1.4418	−5.6736	0.2357	2.8483	0.893	0.942	0.61	0.45
	P_f	−5.7168	2.2613	0.3642	−3.5679	−0.2742	1.9697	0.685	0.791	0.67	0.55
	P_a	−5.0318	3.1186	0.7713	−2.9012	0.8088	1.9931	0.937	0.988	0.38	0.17
	P_r	−6.4083	2.4717	1.6552	−3.6874	0.7230	1.7707	0.957	0.918	0.18	0.25
Hornbeam	P_{st}	3.9075	2.4243	1.0626	−1.5554	0.3737	1.7494	0.792	0.985	0.33	0.09
	P_{br}	−7.3153	3.0262	1.6366	−3.9401	0.1265	2.5415	0.802	0.983	0.44	0.13
	P_f	−7.0979	1.9816	1.6006	−3.9542	−0.6553	2.3679	0.682	0.854	0.48	0.33
	P_a	−4.1476	2.5390	1.2478	−1.4655	0.2157	2.0042	0.791	0.985	0.37	0.10
	P_r	−	−	−	−	−	−	−	−	−	−

(Continued)

TABLE 3 Characteristics of equations (1) and (2)

Genus (subgenus, species)	Biomass component	Coefficients of equations (1)			Coefficients of equations (2)			adjR² for equations[a]		SE for equations[a]	
		a_0	a_1	a_2	a_0	a_1	a_2	(1)	(2)	(1)	(2)
Robinia pseudoacacia	P_{st}	−6.0328	3.5274	0.2219	−4.0119	1.3945	1.6113	0.984	0.996	0.26	0.13
	P_{br}	−8.5599	3.4521	1.0172	−5.2263	0.0784	2.8013	0.946	0.954	0.55	0.51
	P_f	−6.1747	2.1115	0.7108	−3.0012	−1.1741	2.6220	0.897	0.936	0.48	0.38
	P_a	−5.8102	3.4556	0.3645	−3.5233	1.0627	1.8515	0.982	0.995	0.28	0.14
	P_r	−6.1182	3.0281	0.3662	−4.1392	0.9728	1.6105	0.969	0.981	0.33	0.26
Willow	P_{st}	−3.5390	1.6770	1.9024	−4.1864	1.3580	1.6113	0.988	0.994	0.21	0.13
	P_{br}	0.1528	−1.8624	4.6239	−3.1373	−1.0773	3.1376	0.977	0.815	0.30	0.85
	P_f	−0.3151	−1.4312	3.2192	−2.4426	−1.0801	2.2967	0.954	0.730	0.29	0.72
	P_a	−1.6299	0.6277	2.6254	−3.0444	0.6430	1.9808	0.992	0.992	0.17	0.15
	P_r	–	–	–	–	–	–	–	–	–	–
Maple	P_{st}	−6.9220	3.8389	0.5222	−3.1195	0.7518	2.0143	0.929	0.976	0.30	0.18
	P_{br}	−7.6969	2.5504	2.0788	−2.4281	−1.4429	3.4399	0.927	0.912	0.36	0.39
	P_f	−7.4557	2.1207	1.4187	−3.8158	−0.6443	2.3695	0.930	0.920	0.26	0.28
	P_a	−6.5798	3.6755	0.7345	−2.4723	0.3710	2.2604	0.941	0.989	0.28	0.12
	P_r	–	–	–	–	–	–	–	–	–	–
Elm	P_{st}	−5.2055	2.7644	1.2447	−3.5097	1.0983	1.7758	0.927	0.980	0.33	0.17
	P_{br}	−7.0025	2.1650	2.4414	−4.1147	0.4877	2.1442	0.961	0.921	0.24	0.34
	P_f	−6.7639	1.8773	1.4925	−5.4620	2.3035	0.0889	0.950	0.831	0.21	0.39
	P_a	−4.7737	2.6275	1.4102	−2.9461	1.0683	1.7356	0.944	0.980	0.28	0.17

(*Continued*)

TABLE 3 Characteristics of equations (1) and (2)

Genus (subgenus, species)	Biomass component	Coefficients of equations (1)			Coefficients of equations (2)			adjR² for equations[a]		SE for equations[a]	
		a_0	a_1	a_2	a_0	a_1	a_2	(1)	(2)	(1)	(2)
Chosenia	P_r	–	–	–	–	–	–	–	–	–	–
	P_{st}	−7.3317	3.8444	0.4270	−4.4885	1.4131	1.6960	0.923	0.995	0.38	0.09
	P_{br}	−4.1351	1.8236	0.8807	−0.4475	−3.2605	4.3129	0.894	0.860	0.95	0.54
	P_f	−4.5567	1.6765	0.4596	−2.5482	−1.7183	2.9793	0.924	0.928	0.66	0.30
	P_a	−7.0189	3.6925	0.6273	−3.3942	0.7574	2.0369	0.897	0.997	0.43	0.07
Hawthorn	P_r	–	–	–	–	–	–	–	–	–	–
	P_{st}	−1.2128	−0.4783	2.8221	−2.0458	0.4938	1.1043	0.817	0.981	0.18	0.13
	P_{br}	−8.6108	3.7923	4.2467	−1.3277	−1.6520	3.0043	0.796	0.872	0.53	0.51
	P_f	−4.7779	0.0136	4.8245	−1.9927	−1.7531	2.5305	0.750	0.972	0.41	0.17
	P_a	−2.7008	0.6191	3.7607	−0.8785	−0.4459	1.8918	0.846	0.992	0.27	0.10
Prunus sylvestris	P_r	–	–	–	–	–	–	–	–	–	–
	P_{st}	−3.4476	1.1458	2.8662	−5.0280	3.2890	0.5714	0.995	0.985	0.10	0.19
	P_{br}	−2.9426	−0.1337	4.0271	−0.1812	−2.4202	2.6795	0.885	0.993	0.56	0.14
	P_f	−4.3872	1.2171	1.7441	−4.0525	1.0991	0.8809	0.957	0.996	0.22	0.07
	P_a	−2.7142	1.0709	2.8082	−2.6131	1.4371	1.1765	0.978	0.994	0.21	0.12
Juglans mandshurica	P_r	–	–	–	–	–	–	–	–	–	–
	P_{st}	−10.6102	3.0941	3.2584	−3.8386	0.9762	2.0147	0.921	0.994	0.38	0.11
	P_{br}	−10.4918	1.7032	4.2788	−3.5102	0.5692	1.7373	0.954	0.924	0.24	0.31

(Continued)

TABLE 3 Characteristics of equations (1) and (2)

Genus (subgenus, species)	Biomass component	Coefficients of equations (1)			Coefficients of equations (2)			adjR² for equations[a]		SE for equations[a]	
		a_0	a_1	a_2	a_0	a_1	a_2	(1)	(2)	(1)	(2)
	P_f	−7.9616	0.9044	3.4339	−2.4528	0.0720	1.3514	0.971	0.918	0.13	0.22
	P_a	−9.7935	2.7308	3.4642	−2.9214	0.7603	1.9869	0.930	0.996	0.34	0.08
	P_r	–	–	–	–	–	–	–	–	–	–
Maackia	P_{st}	−4.2270	0.6069	3.8326	−1.3153	0.0631	1.9938	0.879	0.958	0.41	0.24
	P_{br}	−3.8711	−0.4487	4.5136	−0.8970	−0.6933	2.1472	0.856	0.876	0,43	0.40
	P_f	−2.8587	−0.7695	3.3428	−0.4013	−1.1676	1.7003	0.854	0.967	0.29	0.14
	P_a	−3.3730	0.3118	3.9561	−0.4711	−0.1598	2.0125	0.876	0.945	0.40	0.27
	P_r	–	–	–	–	–	–	–	–	–	–
Phellodendron amurense	P_{st}	−6.3956	2.6980	1.7243	−2.8406	0.7836	1.7956	0.921	0.987	0.39	0.15
	P_{br}	−8.5992	1.1436	4.2409	−1.2330	−1.8452	3.2566	0.902	0.988	0.42	0.14
	P_f	−1.5724	0.2913	0.9945	−0.0255	−0.1695	0.6018	0.914	0.851	0.09	0.12
	P_a	−5.7480	2.3121	2.0624	−1.7304	0.3150	1.9503	0.919	0.993	0.37	0.11
	P_r	–	–	–	–	–	–	–	–	–	–

[a]Herein after SE is standard error of equations.

TABLE 4 Averaged values of adjR^2 and SE, characterizing the equations (1) and (2) for biomass components P_i, and estimating their differences in relation to the mentioned equations

>Biomass compo-nent	Index	Equation number	M	$\pm m$	Significance of differences by Student		n	Are differences significant?
					t_{act}	t_{stand}		
Coniferous species								
P_{st}	R^2	(1)	0.957	0.0091	2.83	2.14	8	Yes
		(2)	0.984	0.0023				
	SE	(1)	0.321	0.0450	1.45	2.14	8	No
		(2)	0.231	0.0425				
P_{br}	R^2	(1)	0.867	0.0320	0.84	2.14	8	No
		(2)	0.898	0.0184				
	SE	(1)	0.504	0.0563	0.08	2.14	8	No
		(2)	0.511	0.0743				
P_f	R^2	(1)	0.765	0.0637	1.28	2.14	8	No
		(2)	0.857	0.0342				
	SE	(1)	0.516	0.0699	0.42	2.14	8	No
		(2)	0.471	0.0811				
P_a	R^2	(1)	0.942	0.0143	2.46	2.14	8	Yes
		(2)	0.978	0.0037				
	SE	(1)	0.341	0.0514	1.30	2.14	8	No
		(2)	0.249	0.0494				
P_r	R^2	(1)	0.829	0.0583	0.99	2.23	6	No
		(2)	0.900	0.0424				
	SE	(1)	0.530	0.0906	0.37	2.23	6	No
		(2)	0.477	0.1122				
In average	R^2	(1)	0.872	0.0355	1.26	2.00	38	No
		(2)	0.923	0.0202				
	SE	(1)	0.443	0.0626	0.57	2.00	38	No
		(2)	0.388	0.0719				
Small-leaved species								
Pst	R^2	(1)	0.937	0.0146	3.62	2.06	13	Yes
		(2)	0.990	0.0019				
	SE	(1)	0.317	0.0189	8.23	2.06	13	Yes
		(2)	0.132	0.0121				
Pbr	R^2	(1)	0.888	0.0237	1.22	2.06	13	No
		(2)	0.921	0.0125				
	SE	(1)	0.544	0.0541	1.29	2.06	13	No
		(2)	0.454	0.0444				
Pf	R^2	(1)	0.839	0.0324	0.75	2.06	13	No
		(2)	0.870	0.0248				
	SE	(1)	0.488	0.0449	1.22	2.06	13	No
		(2)	0.415	0.0397				

(*Continued*)

TABLE 4 Averaged values of adjR^2 and SE, characterizing the equations (1) and (2) for biomass components P_i, and estimating their differences in relation to the mentioned equations

>Biomass component	Index	Equation number	M	$\pm m$	Significance of differences by Student t_{act}	t_{stand}	n	Are differences significant?
Pa	R^2	(1)	0.927	0.0150	3.42	2.06	13	Yes
		(2)	0.983	0.0063				
	SE	(1)	0.353	0.0319	3.60	2.06	13	Yes
		(2)	0.174	0.0383				
Pr	R^2	(1)	0.856	0.0757	1.41	2.45	4	No
		(2)	0.965	0.0158				
	SE	(1)	0.408	0.1035	1.90	2.45	4	No
		(2)	0.203	0.0304				
In average	R^2	(1)	0.890	0.0323	1.63	1.98	56	No
		(2)	0.946	0.0123				
	SE	(1)	0.422	0.0506	2.42	1.98	56	Yes
		(2)	0.276	0.0330				
Coniferous and small-leaved species								
P_{st}	R^2	(1)	0.945	0.0097	4.36	2.02	21	Yes
		(2)	0.988	0.0016				
	SE	(1)	0.319	0.0201	5.21	2.02	21	Yes
		(2)	0.170	0.0203				
P_{br}	R^2	(1)	0.880	0.0187	1.50	2.02	21	No
		(2)	0.912	0.0105				
	SE	(1)	0.529	0.0391	0.96	2.02	21	No
		(2)	0.476	0.0388				
P_f	R^2	(1)	0.811	0.0316	1.45	2.02	21	No
		(2)	0.865	0.0197				
	SE	(1)	0.499	0.0376	1.16	2.02	21	No
		(2)	0.437	0.0387				
P_a	R^2	(1)	0.933	0.0106	4.23	2.02	21	Yes
		(2)	0.981	0.0041				
	SE	(1)	0.349	0.0270	3.58	2.02	21	Yes
		(2)	0.202	0.0306				
P_r	R^2	(1)	0.840	0.0438	1.68	2.10	10	No
		(2)	0.926	0.0273				
	SE	(1)	0.481	0.0675	1.09	2.10	10	No
		(2)	0.367	0.0795				
In average	R^2	(1)	0.882	0.0229	2.02	1.96	94	Yes
		(2)	0.934	0.0126				
	SE	(1)	0.435	0.0383	1.85	1.96	94	No
		(2)	0.330	0.0416				

Notes. M, the average value of index; m, error of the mean value; t_{act} и t_{stand}, Student's criteria, the actual and table values, respectively; n, the number of equations.

crown, because the measurement precision of the last is incomparably less than the measuring precision of stem diameter, and the determination coefficients, respectively, in the first case are above. However, the proportion of the residual variability is quite high: in the first case, at the expense of ignoring the age of a tree, and in the second case, by ignoring the crown length. In both the cases, the proportion of the residual variability is high in relation to the total variability. As a result, differences of equations (1) and (2) on the value of explained variability (R^2) are statistically not significant. A similar explanation applies to the explained variability of root biomass, but in this case, the uncertainty in the difference R^2 of equations (1) and (2) is compounded by different share of the posted roots in their total biomass, which varies with different measurement methods.

Height and diameter of the stem are stereometrically almost functionally determining its volume (and therefore biomass), so the proportion of the residual variance for stem biomass in equation (2) is minimal compared with the residual variance of equation (1). Accordingly, the explanatory ability to stem biomass by two regressors—height and diameter—is at the statistically significant level much higher than explanatory ability of the combination of tree height and crown width. Because the stem biomass is a predominant share in aboveground one, the statistical significance of the difference of equations (1) and (2) for aboveground biomass as accounted by R^2 gets an explanation by analogy with the biomass of only stem.

4 | CONCLUSIONS

First, for the forests of Eurasia, the database on single tree biomass in a number of about 7.3 thousand measurements is compiled. Only the one-third part of the database has measurements of crown diameter. It is used for comparative analysis of explanatory ability of allometric models intended for estimating tree biomass structure by remote sensing methods using the two most informative morphometric indices of trees - tree height and crown diameter, and traditional allometric models intended for terrestrial inventory of biomass using morphometric indices such as tree height and stem diameter at breast height.

Thus, for the first time a system of allometric models for remote sensing of tree and shrubs biomass structure in the forests of Eurasia is developed. It is found that the explanatory capacity of equations (1) in comparison with (2) for foliage, branches and roots is lower, but this difference is not statistically significant. The same capacity for the stem and aboveground biomass is lower too but this difference is statistically significant. Models (1) and (2) are designed for two different methods of taxation and cannot replace one another.

However, this lower explanatory ability of the first model offsets with above mentioned advantage of laser measurements, the rate of that is much more quickly and not comparable with the traditional terrestrial processing. This makes it possible to assess quickly and relatively accurately the changing carbon pool of forest ecosystems of a given territory during its periodic overflights.

The proposed information can be useful when implementing activities on climate stabilization, as well as in the validation of the results of the simulations on the carbon-depositing capacity of forests.

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