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Double Harmonization of Transcontinental Allometric Model of *Picea* spp.

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Abstract: For the first time the trans-Eurasian additive allometric mixed-effects model of tree biomass components (stems, branches, needles and roots) is designed using the database unique in terms of its volume in a number of 900 model trees of five species of *Picea* spp. taken on sample plots within species from natural habitats in Eurasia. The problem of double harmonization of the model was first solved, in the structure of that two approaches are combined, both in ensuring the principle of additivity of biomass components and in involving into the model the block of dummy variables localizing it along eco-regions of Eurasia. Trivial model involving the dummy and numeric (stem diameter at breast height and the tree height) variables in allometric equations without additivity components gives biomass estimates harmonized according to eco-regions but differing by the absolute value of the mass components only. The fundamental distinction and advantage of the developed model of double harmonization is that unlike of trivial mixed-effects model, it provides compatibility and difference by eco-regions not only of absolute values of biomass components, but also of their ratios, i.e. reflects regional traits of biomass component structure.

Keywords: Biosphere role of forests, Biomass component additivity, Mixed-effects model

Allometric models of single-tree biomass as a basis of taxation standards, intended to estimating biological productivity of forests, are characterized by some uncertainties, and therefore a problem of harmonization of regression models, including allometric ones, is originated. The greatest development received at least two methods, or the two procedures of their harmonization, namely associated respectively with the introduction of "dummy" variables and the implementation of principle of additivity of biomass components. The first method is used to harmonize the characteristics of equations having a number of separate levels. For example, the dependency tree biomass upon stem diameter ($P \sim D$) in different edaphic conditions will have different values of the regression coefficients. When having the aim to harmonize them, in the equation along with numerical variable (in this case D) a block of artificial variables (dummy- or indicator variables), that encodes the equations related to one or another type of forests, is introduced. There are quite a few works dedicated to designing such models (Li and Zhang 2010, Fu et al 2012, Zeng 2015, Usoltsev et al 2017). Lately the equation with a combination of numerical and dummy variables are included in the category of mixed-effects models. With respect to the assessment of tree biomass, the model that includes a combination of numerical and dummy variables has the form

(Fu et al 2012). The second method harmonization was developed in response to the need to harmonize the equations calculated for different biomass components. This uncertainty was noted already in the first works devoted to the evaluation of tree biomass by means of equations involving the two main dendrometric indicators, namely stem diameter D and tree height H (Young et al 1964). It is in violation of the principle of additivity, according to which the total biomass (stem, branches, foliage, roots), obtained from component equations, should be equal (but usually not equal) to the value obtained using the equation for total biomass.

A special review devoted to the history of development of regression equations of additive biomass, starting from the very first works (Kurucz 1969, Kozak 1970), which was examined two methods of harmonization in terms of additivity, based on alternative algorithms: respectively "from particular - to general" and "from general - to particular" (Usoltsev 2017). The method "from general - to particular" harmonizing tree biomass components in terms of additivity was proposed in China (Tang et al 2000, Dong et al 2015). It is based on the principle of disaggregating (disaggregation model) or on a scheme of three-step proportional weighting – 3SPW. The details of the disaggregation principle in the sequence "from general - to

particular”, and its advantages in comparison with the algorithm “from particular - to general” are shown on the example of *Picea* spp. and *Abies* spp. single-trees when designing the additive generic transcontinental model of biomass component composition (Usoltsev et al 2017). In the previous paper (Usoltsev et al 2017) the transcontinental additive generic model of tree biomass for all species *Picea* spp. on overall Eurasia was proposed. In this article on the example of *Picea* spp. tree biomass the first attempt is taken to develop transcontinental allometric model of double harmonization, the structure of which combines both approaches that were above mentioned, namely, the principle of additivity of biomass component composition and the introduction of “dummy” variables, localizing the additive model into regions of Eurasia.

MATERIAL AND METHODS

As a basis of the developed models, the database of single-tree biomass of woody species in Eurasia is used (Usoltsev 2016a,b), from which the data are taken in a number of 900 sample trees of five vicarious species of the genus *Picea* spp., namely *P. abies* (L.) H. Karst., *P. obovata* L., *P. schrenkiana* F. and C.A. Mey., *P. jezoensis* (S.&Z.) Carrière, *P. purpurea* Masters. They are distributed in seven eco-regions and marked respectively by seven dummy variables, from X_0 to X_6 (Table 1). A more detailed description of initial data was represented in our previous publication (Usoltsev 2016 a).

The simple allometry $P_i \sim D$ gives the worst approximation to actual data compared with two-factorial allometry $P_i \sim D, H$, where the diameter (D) and tree height (H) are included in the equation separately, assuming their orthogonality in correct planning of the passive experiment (Nalimov 1971). Accordingly, such two-factorial allometry is widespread in the studies of the tree biomass structure (Battulga et al 2013, Li and Zhao 2013, Cai et al 2013,

Usoltsev 2016 a). Because the measurements of tree height compared to stem diameter is considerably more labour-consuming, regional (Rutishauser et al 2013) or special mixed-effects models $H \sim D$ are developed, which included dummy variables coding different tree species or different site conditions (Valbuena et al 2016). Today, numerous quantities of $H \sim D$ ratios can be obtained using modern techniques that combines forest canopy remote sensing data with terrestrial measurements of trees (Sullivan et al 2017, Lizuka et al 2018).

Two major mass-forming independent variables as predictors - stem diameter and tree height - were included in the allometric tree biomass equation. Attempts to use the additional independent variables related to tree and/or forest stand indices show that they either give a negligible increase of adequacy (Wirth et al 2004), either do not provide it at all (Fu et al 2016). Nevertheless, biomass allometry in pure spruce forests of Europe proved misplaced under the influence of soil conditions (Dutcă et al 2014), and comparison of allometric biomass models, designed on actual data of pure spruce stands and mixed spruce-beech ones, showed significantly lower values in the second case, at the expense of lesser percentage of the spruce crown in aboveground biomass (Dutcă et al 2017).

Because the minimum stem diameter at breast height (DBH) in the compiled database is 0.5-0.6 cm and minimum height 1.4 m, the traditional allometric relationship of tree biomass with DBH and tree height is broken as a result of the shift of taxation diameter up to stem. As a consequence, a correlation of residual dispersion appears, i.e. there is an underestimating of all component biomass at the smallest and most large trees and accordingly is overestimating at mean trees. This is eliminated by the introduction of variable $(\ln D)$ $(\ln H)$, that is statistically significant in all cases (Usoltsev et al 2017). As in previous studies (Usoltsev 2016a), we do not use as a predictor the so-called “form cylinder” D^2H ,

Table 1. The scheme of encoding regional pools of *Picea* tree biomass data with dummy variables

Ecoregion*	Species <i>Picea</i> spp.	Block of dummy variables						Tree DBH range, cm	Tree height range, m	Number of trees
		X_1	X_2	X_3	X_4	X_5	X_6			
WME	<i>P. abies</i>	0	0	0	0	0	0	5.0+68.0	4.2+43.0	359
EPR	<i>P. abies</i>	1	0	0	0	0	0	0.6+51.5	1.5+32.4	183
Ur(nat.)	<i>P. obovata</i>	0	1	0	0	0	0	3.5+38.0	3.2+24.0	40
Ur(plant.)	<i>P. obovata</i>	0	0	1	0	0	0	0.6+17.4	1.4+13.5	276
WS	<i>P. obovata</i>	0	0	0	1	0	0	0.5+6.4	1.5+6.7	7
PT	<i>P. schrenkiana</i>	0	0	0	0	1	0	6.7+43.5	6.8+33.4	15
FE	<i>P. jezoensis, P. purpurea</i>	0	0	0	0	0	1	6.7+30.7	5.8+20.1	10

* WME – Western and Middle Europe; EPR – European part of Russia; Ur(nat.) – Ural, natural forests; Ur(plant.) – Ural, plantations; WS – Western Siberia, forest-steppe; PT – Pamir-Tien Shan province (Northwest China); FE – Far Eastern province (Primorye and North-East China).

because in its structure at the given diameter the dependence of biomass upon tree height is “enforced” positive, whereas when increasing height of trees of equal diameter the crown biomass is reduced by age and cenotical features of stands. Hence the worst explanatory ability of “form cylinder” compared with only DBH that is proven by numerous studies (Ruiz-Peinado et al 2012, Dong et al 2015, Magalhães and Seifert 2015, Bronisz et al 2016, Usoltsev 2016 a). But the result of evaluating the crown biomass improves significantly, when along with the “form cylinder” the crown length index is included into model as the second predictor, which takes into account the mentioned features (Parresol 1999, Carvalho and Parresol 2003).

RESULTS AND DISCUSSION

In the first phase of the mentioned double harmonizing the independent (i.e. not additive) allometric equations are calculated in our study according to the following order (Fig. 1 in: Usoltsev et al 2017): first - for total biomass, then - for the aboveground (intermediate component) and underground biomass (Step 1), then - for intermediate components - tree crown and stem above bark (Step 2) and, finally, for the original (initial) components - needle and branches (Step 3a) and wood and bark of the stem (Step 3b) according to their adopted structure

$$\ln P_i = a_i + b_i(\ln D) + c_i(\ln H) + d_i(\ln D)(\ln H) + \sum e_{ij} X_j \quad (2)$$

где e_i – designation of biomass components: total (t), aboveground (a), roots (r), tree crown (c), stem above bark (s), foliage (f), branches (b), stem wood (w) and stem bark (bk); j – code of dummy variable, from 0 to 6 (Table 1). $\sum e_{ij} X_j$ – the block of dummy variables for i -th biomass component of j -th eco-region. The model (2) after the anti-log circuits has the form

$$P_i = e^{a_i} D^{b_i} H^{c_i} D^{d_i(\ln H)} e^{\sum e_{ij} X_j} \quad (3)$$

Calculation of coefficients of initial equations (2) is made using the program of common regression analysis, and their characteristics are obtained that after correcting on logarithmic transformation by Baskerville (1972) and transforming their to the form (3) are shown in the Table 2. All the regression coefficients for numerical variables in equations (3) are significant at the level of probability $P_{0.95}$ or higher, and the equations are adequate to harvest data. Structure of additive model proposed by Chinese researchers (Tang et al 2000, Dong et al 2015), is modified in accordance with the character traits of research and is shown in Figure 1.

In the second phase of our research, by involving the regression coefficients of independent equations from Table 2 into the structure of the additive model, presented in Figure 1, we obtain the transcontinental three-step additive model of

Step 1	P_r	$\frac{1}{a_a D^{ba} H^{ca} D^{da} (\ln H) e^{eajxj}}$	P_t
	1	$\frac{a_r D^{br} H^{cr} D^{dr} (\ln H) e^{erjxj}}{a_a D^{ba} H^{ca} D^{da} (\ln H) e^{eajxj}}$	
Step 2	P_r	$\frac{1}{a_s D^{bs} H^{cs} D^{ds} (\ln H) e^{esjxj}}$	P_t
	1	$\frac{a_c D^{bc} H^{cc} D^{dc} (\ln H) e^{ecjxj}}{a_s D^{bs} H^{cs} D^{ds} (\ln H) e^{esjxj}}$	
Step 3a	P_r	$\frac{1}{a_b D^{bb} H^{cb} D^{db} (\ln H) e^{ebjxj}}$	P_t
	1	$\frac{a_f D^{bf} H^{cf} D^{df} (\ln H) e^{efjxj}}{a_b D^{bb} H^{cb} D^{db} (\ln H) e^{ebjxj}}$	
Step 3b	P_r	$\frac{1}{a_{bk} D^{bbk} H^{cbk} D^{dbk} (\ln H) e^{ebbkjxj}}$	P_t
	1	$\frac{a_w D^{bfw} H^{cfw} D^{dfw} (\ln H) e^{ewjxj}}{a_{bk} D^{bbk} H^{cbk} D^{dbk} (\ln H) e^{ebbkjxj}}$	

Fig. 1. The structure of three-step additive model designed under proportional weighting. Symbols here and further see in equation (2)

biomass component composition designed under proportional weighting scheme (Fig. 2). The final appearance of this model of double harmonization is shown on the Fig. 3.

The model is valid in the range of harvest data of stem height and DBH of sample trees shown in Table 1. Tabulating the obtained final model (Fig. 3) on the given values of D and H , as well as on the dummy variables localizing the total model according to eco-regions, gives as a result, regional regulations, additive on biomass components and designed to spruce biomass estimating on Eurasia. Taking into account the labour intensity, and sometimes the impossibility of measuring the heights of trees in the wild, we additionally design the auxiliary equation for calculating the biomass on the unit area of a forest stand with the application of the proposed additive biomass model:

$$H = 1.2 D^{0.9128} e^{0.4364(1/D)} e^{-0.0445X1} e^{-0.1947X2} e^{-0.1405X3} e^{-0.0290X4} e^{-0.0118X5} e^{-0.2939X6}, \quad (4)$$

Table 2. The characteristic of independent (initial)allometric equations (3).

Biomass component	Independent variables and regression coefficients of the model										adjR ^{2*}	SE*
P _t	0.5236	D ^{0.9170}	H ^{0.1114}	D ^{0.3210(lnH)}	e ^{-0.0837X1}	e ^{0.0436X2}	e ^{0.2655X3}	e ^{0.1163X4}	e ^{0.0598X5}	e ^{0.1590X6}	0.990	1.19
Step 1												
P _a	0.6650	D ^{0.9268}	H ^{-0.1407}	D ^{0.3461(lnH)}	e ^{-0.1197X1}	e ^{0.0390X2}	e ^{-0.0396X3}	e ^{-0.2369X4}	e ^{0.1701X5}	e ^{0.1364X6}	0.986	1.26
P _r	0.0725	D ^{0.9393}	H ^{-0.1659}	D ^{0.4236(lnH)}	e ^{0.3392X1}	e ^{0.2134X2}	e ^{0.6642X3}	e ^{0.8177X4}	e ^{0.3315X5}	e ^{0.4874X6}	0.975	1.44
Step 2												
P _c	0.4809	D ^{1.6489}	H ^{-1.1713}	D ^{0.2887(lnH)}	e ^{0.0268X1}	e ^{0.4637X2}	e ^{0.3302X3}	e ^{-0.1674X4}	e ^{0.2536X5}	e ^{-0.0107X6}	0.930	1.53
P _s	0.2343	D ^{0.6682}	H ^{0.4936}	D ^{0.3223(lnH)}	e ^{-0.1357X1}	e ^{-0.0855X2}	e ^{-0.2480X3}	e ^{-0.1305X4}	e ^{0.1852X5}	e ^{0.2759X6}	0.992	1.22
Step 3a												
P _f	0.2817	D ^{1.6561}	H ^{-1.2510}	D ^{0.2831(lnH)}	e ^{0.0115X1}	e ^{0.3919X2}	e ^{0.3107X3}	e ^{-0.3497X4}	e ^{0.3013X5}	e ^{-0.3989X6}	0.904	1.62
P _b	0.2054	D ^{1.6372}	H ^{-1.1094}	D ^{0.2987(lnH)}	e ^{-0.1494X1}	e ^{0.6184X2}	e ^{0.3768X3}	e ^{0.1097X4}	e ^{0.2840X5}	e ^{0.3309X6}	0.887	1.78
Step 3b												
P _w	0.2484	D ^{0.73414}	H ^{0.3360}	D ^{0.3286(lnH)}	e ^{0.0061X1}	e ^{-0.1181X2}	e ^{-0.4134X3}	e ^{-0.5122X4}	e ^{0.1427X5}	e ^{0.1640X6}	0.991	1.23
P _{bk}	0.0441	D ^{0.7639}	H ^{0.1592}	D ^{0.2944(lnH)}	e ^{0.0172X1}	e ^{0.1567X2}	e ^{-0.0368X3}	e ^{0.5045X4}	e ^{0.5520X5}	e ^{0.7337X6}	0.976	1.34

*adj R² – coefficient of determination adjusted for the number of observations; SE – standard error of equations in the initial dimension P_i(kg).

		$P_t = 0.5236 D^{0.9170} H^{0.1114} D^{0.3210(\ln H)} e^{-0.0837X1} e^{0.0436X2} e^{0.2655X3} e^{0.1163X4} e^{0.0598X5} e^{0.1590X6}$											
Step 1	$P_a =$	1										$\times P_t$	
	1+	$0.0725 D^{0.9393} H^{-0.1659} D^{0.4236(\ln H)} e^{0.3392X1} e^{0.2134X2} e^{0.6642X3} e^{0.8177X4} e^{0.3315X5} e^{0.4874X6}$											
		$0.6650 D^{0.9268} H^{-0.1407} D^{0.3461(\ln H)} e^{-0.1197X1} e^{0.0390X2} e^{-0.0396X3} e^{-0.2369X4} e^{0.1701X5} e^{0.1364X6}$											
	$P_r =$	1										$\times P_t$	
	1+	$0.6650 D^{0.9268} H^{-0.1407} D^{0.3461(\ln H)} e^{-0.1197X1} e^{0.0390X2} e^{-0.0396X3} e^{-0.2369X4} e^{0.1701X5} e^{0.1364X6}$											
		$0.0725 D^{0.9393} H^{-0.1659} D^{0.4236(\ln H)} e^{0.3392X1} e^{0.2134X2} e^{0.6642X3} e^{0.8177X4} e^{0.3315X5} e^{0.4874X6}$											
Step 2	$P_c =$	1										$\times P_a$	
	1+	$0.2343 D^{0.6682} H^{0.4936} D^{0.3223(\ln H)} e^{-0.1357X1} e^{-0.0855X2} e^{-0.2480X3} e^{-0.1305X4} e^{0.1852X5} e^{0.2759X6}$											
		$0.4809 D^{1.6489} H^{-1.1713} D^{0.2887(\ln H)} e^{0.0268X1} e^{0.4637X2} e^{0.3302X3} e^{-0.1674X4} e^{0.2536X5} e^{-0.0107X6}$											
	$P_s =$	1										$\times P_a$	
	1+	$0.4809 D^{1.6489} H^{-1.1713} D^{0.2887(\ln H)} e^{0.0268X1} e^{0.4637X2} e^{0.3302X3} e^{-0.1674X4} e^{0.2536X5} e^{-0.0107X6}$											
		$0.2343 D^{0.6682} H^{0.4936} D^{0.3223(\ln H)} e^{-0.1357X1} e^{-0.0855X2} e^{-0.2480X3} e^{-0.1305X4} e^{0.1852X5} e^{0.2759X6}$											
Step 3a	$P_f =$	1										$\times P_c$	
	1+	$0.2054 D^{1.6372} H^{-1.1094} D^{0.2987(\ln H)} e^{-0.1494X1} e^{0.6184X2} e^{0.3768X3} e^{0.1097X4} e^{0.2840X5} e^{0.3309X6}$											
		$0.2817 D^{1.6561} H^{-1.2510} D^{0.2831(\ln H)} e^{0.0115X1} e^{0.3919X2} e^{0.3107X3} e^{-0.3497X4} e^{0.3013X5} e^{-0.3989X6}$											
	$P_b =$	1										$\times P_c$	
	1+	$0.2817 D^{1.6561} H^{-1.2510} D^{0.2831(\ln H)} e^{0.0115X1} e^{0.3919X2} e^{0.3107X3} e^{-0.3497X4} e^{0.3013X5} e^{-0.3989X6}$											
		$0.2054 D^{1.6372} H^{-1.1094} D^{0.2987(\ln H)} e^{-0.1494X1} e^{0.6184X2} e^{0.3768X3} e^{0.1097X4} e^{0.2840X5} e^{0.3309X6}$											
Step 3b	$P_w =$	1										$\times P_s$	
	1+	$0.0441 D^{0.7639} H^{0.1592} D^{0.2944(\ln H)} e^{0.0172X1} e^{0.1567X2} e^{-0.0368X3} e^{0.5045X4} e^{0.5520X5} e^{0.7337X6}$											
		$0.2484 D^{0.73414} H^{0.3360} D^{0.3286(\ln H)} e^{0.0061X1} e^{-0.1181X2} e^{-0.4134X3} e^{-0.5122X4} e^{0.1427X5} e^{0.1640X6}$											
	$P_{bk} =$	1										$\times P_s$	
	1+	$0.2484 D^{0.73414} H^{0.3360} D^{0.3286(\ln H)} e^{0.0061X1} e^{-0.1181X2} e^{-0.4134X3} e^{-0.5122X4} e^{0.1427X5} e^{0.1640X6}$											
		$0.0441 D^{0.7639} H^{0.1592} D^{0.2944(\ln H)} e^{0.0172X1} e^{0.1567X2} e^{-0.0368X3} e^{0.5045X4} e^{0.5520X5} e^{0.7337X6}$											

Fig. 2. The additive combination of the original analytical dependencies of component biomass upon tree height and DBH, calculated according to the principle of proportional weighing

adjR² = 0.958; SE = 0.16.

Variable (1/D) is introduced in the model structure (4) for the allometry correction, broken in small trees due to the shift of measurement of diameter *D* in the upper part of the crown. Because the volume of taxation tables exceeds the format of journal article, we will focus on analyzing some of regional characteristics of the spruce biomass structure of equal size trees on the relevant table fragments (Table 3). Primarily, the Ural region is of our interest where within the south taiga subzone we have two pools of sample trees *Piceaobovata*, data of which were obtained, respectively, in natural stands and plantations. A comparative analysis of the biomass structure of equal size trees (within the range of applicability of the model, as shown in Table 1) showed significant excess of tree biomass in plantations, namely, total, aboveground and underground biomass on 24, 14 and 88 percent respectively. The proportion of needles in the aboveground biomass varies slightly (13 and 15%, respectively), but the difference in root: shoot ratio is significant. The latter is in natural stands and plantations 0.22 and 0.37, respectively.

Spruce trees of two regions adjacent to the Pacific (*P. jezoensis*) and Atlantic (*P. abies*) Oceans differ significantly in the structure of their biomass: exceeding the first over the second is for total, aboveground and underground biomass on 17, 10 and 56percent respectively. The proportion of needles in the aboveground biomass is 5 and 10percent, respectively, and the root: shoot ratio is 0.26 0.18 respectively. Structure of tree biomass on two more distant

regions (Pamir-TienShan province and European part of Russia) and of species growing on their territories (*P. schrenkiana* and *P. abies* respectively) also varies considerably: the difference between the first and the second is accounted for to total, aboveground and underground biomass 15, -9 and 22 percent respectively. The root: shoot ratio equal to 0.21 and 0.29, respectively, and there are no differences in the proportion of needles in the aboveground biomass (11%).

It was shown by some researchers (Cunia and Briggs 1984, Reed and Green 1985), that the removal of internal inconsistency of equations for tree biomass by ensuring their additivity does not necessarily mean any improvements in the accuracy of its estimates. Therefore it is necessary to clear whether adequate an additive model obtained and how its adequacy characteristics are comparable with those of the independent equations? To this purpose, the biomass estimates obtained using independent and additive equations are compared with observed biomass values in the database by calculating the coefficient of determination *R*² and the root mean squared error *RMSE* in accordance of the formulas

$$R^2 = 1 - \frac{\sum_{i=1}^N (Y_i - \bar{Y}_i)^2}{\sum_{i=1}^N (Y_i - \bar{Y}_i)^2} \quad RMSE = \frac{\sum_{i=1}^N (Y_i - \bar{Y}_i)^2}{P} \quad (5)$$

Where *Y_i* is observed value; *Y_j* predicted value; \bar{Y} is the mean of *N* observed values for the same component; *p* is the number of model parameters; *N* is sample size of trees

		$Pt = 0.5236 D^{0.9170} H^{0.1114} D^{0.3210(\ln H)} e^{-0.0837X1} e^{0.0436X2} e^{0.2655X3} e^{0.1163X4} e^{0.0598X5} e^{0.1590X6}$										
Step 1	<i>Pa</i> =	1										× <i>Pt</i>
		$1+0.1090 D^{-0.0125} H^{0.0252} D^{0.0775(\ln H)} e^{-0.4589X1} e^{-0.1744X2} e^{-0.7038X3} e^{1.0546X4} e^{-0.1614X5} e^{-0.3510X6}$										
	<i>Pr</i> =	1										× <i>Pt</i>
		$1+9.1724 D^{-0.0125} H^{0.0252} D^{-0.0775(\ln H)} e^{-0.4589X1} e^{-0.1744X2} e^{-0.7038X3} e^{-1.0546X4} e^{-0.1614X5} e^{-0.3510X6}$										
Step 2	<i>Pc</i> =	1										× <i>Pa</i>
		$1+0.4872 D^{-0.9807} H^{1.6649} D^{0.0336(\ln H)} e^{-0.1625X1} e^{-0.5492X2} e^{-0.5782X3} e^{0.0369X4} e^{-0.0684X5} e^{0.2866X6}$										
	<i>Ps</i> =	1										× <i>Pa</i>
		$1+2.0525 D^{0.9807} H^{-1.6649} D^{-0.0336(\ln H)} e^{-0.1625X1} e^{0.5592X2} e^{0.5782X3} e^{-0.0369X4} e^{-0.0684X5} e^{-0.2866X6}$										
Step 3a	<i>Pf</i> =	1										× <i>Pc</i>
		$1+0.7291 D^{-0.0189} H^{0.1416} D^{0.0156(\ln H)} e^{-0.1379X1} e^{0.2265X2} e^{0.0661X3} e^{0.4594X4} e^{-0.0173X5} e^{0.7298X6}$										
	<i>Pb</i> =	1										× <i>Pc</i>
		$1+1.3715 D^{0.0189} H^{-0.1416} D^{-0.0156(\ln H)} e^{-0.1379X1} e^{-0.2265X2} e^{-0.0661X3} e^{-0.4594X4} e^{0.0173X5} e^{-0.7298X6}$										
Step 3b	<i>Pw</i> =	1										× <i>Ps</i>
		$1+0.1775 D^{0.0298} H^{-0.1768} D^{-0.0342(\ln H)} e^{0.0111X1} e^{0.2748X2} e^{0.3766X3} e^{1.0167X4} e^{0.4093X5} e^{0.5697X6}$										
	<i>Pbk</i> =	1										× <i>Ps</i>
		$1+5.6326 D^{-0.0298} H^{0.1768} D^{0.0342(\ln H)} e^{-0.0111X1} e^{-0.2748X2} e^{-0.3766X3} e^{-1.0167X4} e^{-0.4093X5} e^{-0.5697X6}$										

Fig. 3. Three-step trans-Eurasian additive model of component biomass composition of spruce trees redesigned under proportional weighing scheme

involving into calculating R^2 and $RMSE$.

To properly comparing the adequacy of independent and additive equations, the observed data are given in comparable condition, i.e. independent equations for all biomass components are calculated according to the same

data that the additive equation for the total phytomass (where were exclude the observations without root data). Characteristics of such "methodized" equations is given in the Table 4. The results of the comparison (Table 5) suggest that the additive equations not only internally consistent, but

Table 3. Fragments of the additive biomass (kg) table of trees having DBH of 14 cm and tree height of 14 m in different eco-regions and the corresponding species of genus *Picea* spp

Biomass components, kg	Ecoregion and the corresponding species of genus <i>Picea</i> spp.					
	Ur(plant.) <i>P. obovata</i>	Ur(nat.) <i>P. obovata</i>	FE <i>P. jezoensis</i> , <i>P. purpurea</i>	WME <i>P. abies</i>	PT <i>P. schrenkiana</i>	EPR <i>P. abies</i>
Total biomass	96.36	77.19	86.63	73.89	78.45	67.96
Roots	25.80	13.68	17.71	11.32	13.75	15.12
Above-ground	70.56	63.51	68.92	62.58	64.70	52.84
Crown	22.76	20.08	11.51	13.19	14.38	12.63
Needles	10.34	8.33	3.45	6.21	6.83	5.52
Branches	12.42	11.75	8.05	6.98	7.55	7.11
Stem above bark	47.80	43.43	57.41	49.39	50.31	40.21
Stem wood	42.00	38.61	49.16	45.11	44.02	36.69
Stem bark	5.80	4.82	8.25	4.28	6.29	3.52

Table 4. The characteristic of "methodized" independent allometric equations (3)

Biomass components	Independent variables and regression coefficients of the model									
	P_t	$D^{0.9170}$	$H^{0.1114}$	$D^{0.3210(\ln H)}$	$e^{-0.0837X1}$	$e^{0.0436X2}$	$e^{0.2655X3}$	$e^{-0.1163X4}$	$e^{0.0598X5}$	$e^{0.1590X6}$
Step 1										
P_a	0.4574	$D^{0.9133}$	$H^{0.1438}$	$D^{0.3054(\ln H)}$	$e^{-0.11604X1}$	$e^{0.0248X2}$	$e^{0.1955X3}$	$e^{-0.0223X4}$	$e^{0.0225X5}$	$e^{0.1004X6}$
P_r	0.0731	$D^{0.9405}$	$H^{-0.1699}$	$D^{0.4236(\ln H)}$	$e^{0.3325X1}$	$e^{0.2130X2}$	$e^{0.6597X3}$	$e^{0.8137X4}$	$e^{0.3313X5}$	$e^{0.4858X6}$
Step 2										
P_c	0.3116	$D^{1.5201}$	$H^{-0.6013}$	$D^{0.2170(\ln H)}$	$e^{-0.1713X1}$	$e^{0.4610X2}$	$e^{0.4770X3}$	$e^{-0.0157X4}$	$e^{-0.3839X5}$	$e^{-0.1722X6}$
P_s	0.1985	$D^{0.6511}$	$H^{0.5446}$	$D^{0.3254(\ln H)}$	$e^{-0.1526X1}$	$e^{-0.1169X2}$	$e^{-0.1364X3}$	$e^{0.0118X4}$	$e^{0.1396X5}$	$e^{0.2547X6}$
Step 3a										
P_f	0.1520	$D^{1.6252}$	$H^{-0.8756}$	$D^{0.2518(\ln H)}$	$e^{-0.0288X1}$	$e^{0.4179X2}$	$e^{0.8202X3}$	$e^{-0.0278X4}$	$e^{-0.2530X5}$	$e^{-0.5150X6}$
P_b	0.1429	$D^{1.4219}$	$H^{-0.3226}$	$D^{0.1818(\ln H)}$	$e^{-0.1750X1}$	$e^{0.6198X2}$	$e^{0.2591X3}$	$e^{0.1316X4}$	$e^{-0.3912X5}$	$e^{0.1427X6}$
Step 3b										
P_w	0.2484	$D^{0.73414}$	$H^{0.3360}$	$D^{0.3286(\ln H)}$	$e^{0.0061X1}$	$e^{-0.1181X2}$	$e^{-0.4134X3}$	$e^{-0.5122X4}$	$e^{0.1427X5}$	$e^{0.1640X6}$
P_{bk}	0.0441	$D^{0.7639}$	$H^{0.1592}$	$D^{0.2944(\ln H)}$	$e^{0.0172X1}$	$e^{0.1567X2}$	$e^{-0.0368X3}$	$e^{0.5045X4}$	$e^{0.5520X5}$	$e^{0.7337X6}$

Table 5. The comparison of adequacy indices of independent and additive equations for spruce tree biomass.

Indices	Biomass components*								
	P_t	P_a	P_r	P_s	P_w	P_{bk}	P_c	P_b	P_f
Independent equations									
R^2	0.950	0.902	0.777	0.898	0.943	0.875	0.728	0.800	0.660
RMSE	69.50	88.34	28.72	77.07	33.38	3.82	22.91	13.96	9.19
Additive equations									
R^2	0.950	0.916	0.786	0.914	0.905	0.844	0.825	0.836	0.631
RMSE	69.70	82.12	28.12	70.99	43.08	4.27	18.38	12.64	9.57

* Designations see equation (2). Bold fonts are components, for which the values of R^2 on the additive models higher than on independent ones, and $RMSE$ values respectively below

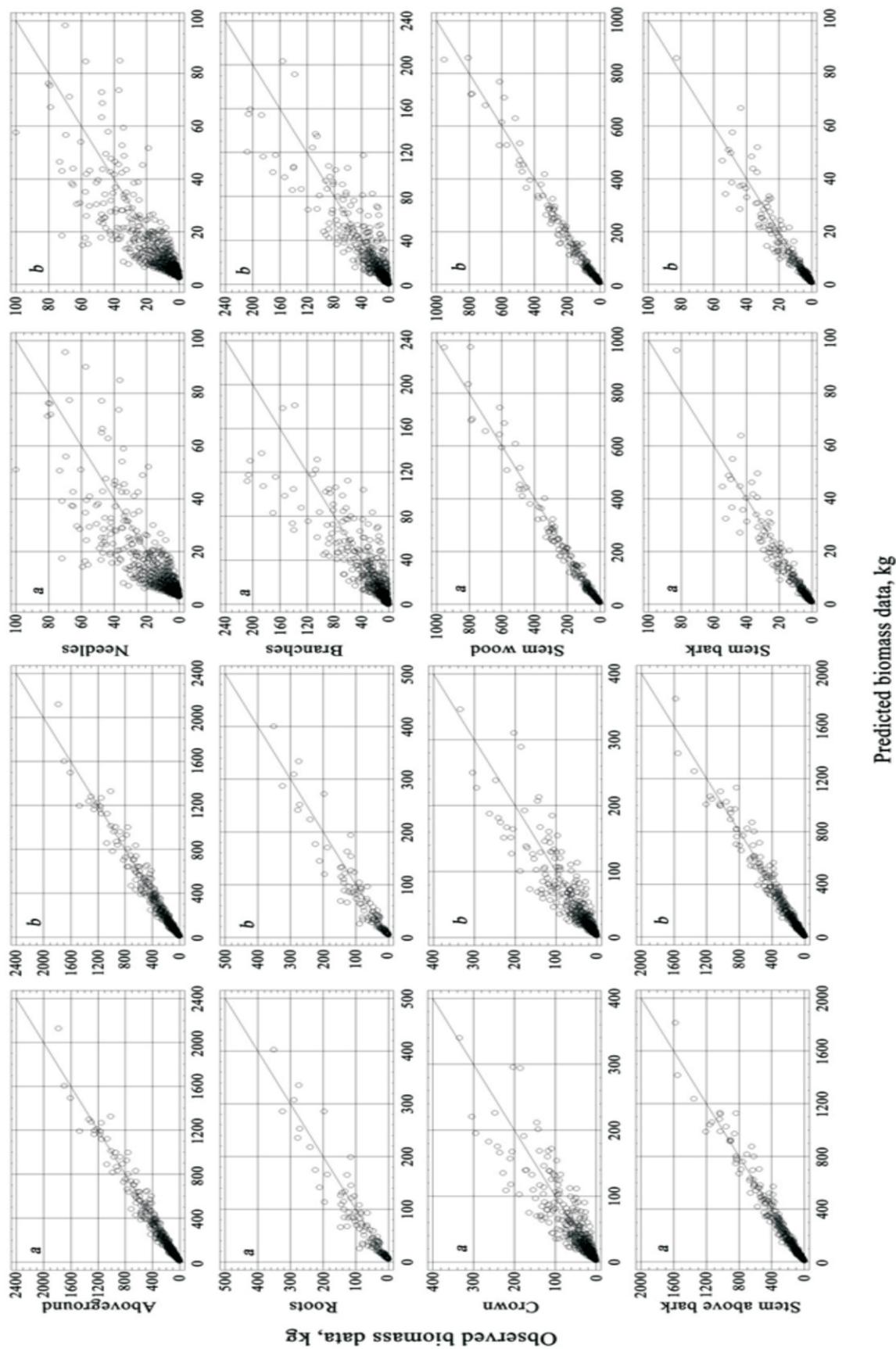


Fig. 4. The ratio of observed values and the values derived by calculation on independent (a) and additive (b) models of tree biomass.

also for the most part of components possess the best indices of adequacy compared with independent equations. The ratio of observed values and the values derived by calculation on independent and additive models of tree biomass (Fig. 4) shows the degree of correlativeness of the above-mentioned indices and the lack of visible differences in the structure of residual variance, obtained in two types of models.

CONCLUSIONS

Thus, for the first time in Russian literature the Trans-Eurasian additive model of tree biomass of five species of genus *Picea* spp. is designed using the unique single-tree database. The model is harmonized in two ways: It eliminates the internal contradictions of the component equations and the total one, and in addition, it takes into account the regional (and, respectively species) differences between trees of equal size both in magnitude of common over ground and underground phytomass and its component structure. Trivial mixed-effects model involving the dummy and numeric variables in allometric equations without component additivity, gives biomass estimates harmonized according to eco-regions only but differing by the absolute value of the biomass components (Fu et al 2012). The fundamental distinction and advantage of the developed model of double harmonization is that unlike of trivial mixed-effects model, it provides compatibility and difference by eco-regions not only of absolute values of biomass fractions, but also of their ratios, i.e. reflects regional characteristics of biomass component structure. Thus belied the assertion by Bi et al. (2004) that features of component structure of the additive model on several separate levels may not be taken into account, resulting in the harmonized characteristics are possible only for total biomass. The proposed model and corresponding tables for estimating tree biomass makes their possible to calculate spruce stand biomass (t/ha) on Eurasian forests when using measuring taxation.

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