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ADDITIVE ALLOMETRIC MODEL OF SINGLE-TREE BIOMASS OF *BETULA* SP. AS A BASIS OF REGIONAL TAXATION STANDARDS FOR EURASIA

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Abstract–When using the unique in terms of the volume of database on the level of a single-tree of the genus *Betula* sp., the trans-Eurasian additive allometric model of biomass of trees for Eurasian birch forests is developed for the first time, and thereby the combined problem of model additivity and generality is solved. The additive model of tree biomass of *Betula* sp. is harmonized in two ways: it eliminated the internal contradictions of the component and the total biomass equations, and in addition, it takes into account regional differences of trees of equal sizes not only on total, aboveground and underground biomass, but also on its component structure, i.e. it reflects the regional peculiarities of the component structure of tree biomass.

INTRODUCTION

The world is experiencing unprecedented forest ecology-scale information splash in estimates of biological productivity and carbon-depositing capacity of forests in the assumption of anthropogenic climate change and finding capacity of his stabilization. In recent years, the scientific branch associated with calculating allometric models of trees and stands in the aspect of their harmonization. Harmonization implies at least two directions: (1) designing of compatible regional models based on dummy variables (Zeng, 2015; Fu *et al.*, 2017) and (2) designing of compatible models based on the principle of additivity of biomass component composition (Parresol, 2001; Dong *et al.*, 2015).

In this article, the first attempt to develop a harmonized allometric transcontinental model of tree biomass, which combined both mentioned by M. Jacobs and T. Cunia (1980) approaches, namely, ensuring the principle of additivity of component composition and localization (unbundling) of additive biomass model on the example of birch (genus *Betula* sp.). according to regions of Eurasia by introducing dummy variables.

MATERIAL AND METHODS

In recent years across all the territory of Eurasia the database on single-tree biomass in a number of 7300 definitions on sample plots was first compiled and published (Usoltsev, 2016). Of the mentioned database the materials in a number of 1076 sample trees of four vicarage species of the genus *Betula* sp. (*B. alba* L., *B. platyphylla* Suk., *B. costata* Trautv. and *B. dahurica* Pall.) are taken, that are distributed in 11 eco-regions and marked respectively by 11 dummy variables from X_0 to X_{10} (Table 1).

Analysis of biomass of tree biomass is made on the basis of allometric additive models. According to the structure of disaggregating three-step additive model system (Tang *et al.*, 2000; Dong *et al.*, 2015), total biomass, estimated by the total equation, exploded into components according to the scheme presented in: (Dong *et al.*, 2015). The coefficients of the regression models for all three steps are evaluated simultaneously, which ensures additivity of the all components: total, intermediate and initial ones (Dong *et al.*, 2015).

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RESULTS AND DISCUSSION

Initial allometric models are calculated;

$\ln P_i = a_i + b_i (\ln D) + c_i (\ln H) + d_i (\ln D)(\ln H) + \Sigma g_{ij} X_j$, (1)

where P_i –biomass of *i*-th component, kg; *D* – diameter on breast height, ñm; Σ – tree height, m; *i* – index of biomass component: 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* - index (code) of dummy variable, from 0 to 10 (see Table 1). $\Sigma g_{ij} X_j$ – block of dummy variables for *i*–th biomass component of *j*–th ecoregion. Model (1) after antilogarithmic procedure has the form

$$P_i = e^{ai} D^{bi} H^{ci} D^{di(\ln H)} e^{\Sigma gijXj}. \quad .. (2)$$

Since calculation of regression coefficients in the model (1) is made in the transformed data, to eliminate biases caused by logarithmic modification of variables, in the equation the amendment proposed by G.L Baskerville (1972) is introduced. Using the programme of common regression analysis the calculation of coefficients of equations (1) is performed and their characteristic is obtained, that is characterized by R^2 in the range 0.904 to 0.994. All the regression coefficients for numerical variables of the equations (2) are significant at the level of probability of 0.95 or higher, and the equations are adequate to empirical data.

When using three-step scheme of proportional weighting (Dong *et al.*, 2015), we got transcontinental additive model of component composition of birch tree biomass of double harmonization, that is given in Table 2. The model is valid in the range of actual data of height and diameter of the sample trees shown in the Table 1.

By tabulating the model obtained (Table 2) according to the given values of *D* and *Í* as well as by the values of the dummy variables, localizing the general model for eco-regions, you can calculate regional transcontinental standards for Eurasia, intended for estimating tree and forest additive biomass components. Because sometimes it is impossible to measure the height of trees in sample plots, for such cases when calculating the biomass per ha the auxiliary equation intended for using the proposed model (2) is calculated, adjusted to logarithmic transformation

$$H = 1.9871\, D^{0.8766}\, e^{0.2804/D}\, e^{-0.0168D}\, e^{0.0235X1} e^{-0.1800X2}\, e^{-0.0274X3}\, e^{0.0114X4}\, e^{-0.4268X5}\, e^{0.1510X6}\, e^{0.0188X7} \times \times e^{-0.0439X8}\, e^{-0.1642X9}\, e^{-0.0024X10};$$

Table 1. The scheme of regional coding actual biomass of 1076 birch sample trees by dummy variables.

Regi-on *	Species of*Betula* sp.	Dummy X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	Number of measurements variables	Range of DBH, cm	Range of tree height, m
WMÅ	*B. alba* L.	0	0	0	0	0	0	0	0	0	0	0.5÷21.0	2.1÷18.8	12
ÅR	*B. alba* L.	**1**	0	0	0	0	0	0	0	0	0	0.9÷41.8	2.2÷27.1	160
Ural	*B. alba* L.	0	**1**	0	0	0	0	0	0	0	0	1.0÷31.0	2.7÷26.4	193
WSst	*B. alba* L.	0	0	**1**	0	0	0	0	0	0	0	0.5÷48.0	1.7÷25.0	571
MS	*B. alba* L.	0	0	0	**1**	0	0	0	0	0	0	0.2÷44.7	1.5÷26.6	64
FEn	*B. platyphylla* S.	0	0	0	0	**1**	0	0	0	0	0	6.7÷27.1	6.6÷14.2	5
FEs	*B. platyphylla* S.	0	0	0	0	0	**1**	0	0	0	0	9.1÷30.5	12.5÷26.0	7
FEs	*B. costata* Tr.	0	0	0	0	0	0	**1**	0	0	0	8.6÷30.2	15.3÷20.9	7
FEs	*B.dahurica* Pall.	0	0	0	0	0	0	0	**1**	0	0	9.8÷30.8	13.7÷20.4	7
Ch	*B. platyphylla* S.	0	0	0	0	0	0	0	0	**1**	0	0.2÷28.0	1.5÷20.0	17
Jap	*B. platyphylla* S.	0	0	0	0	0	0	0	0	0	**1**	4.3÷16.4	7.2÷19.8	33

* Region designations: WMÅ – West and Middle Europe; ÅR – European part of Russia, Central territory; Ural – Midle and Southern Ural; WSst – Western Siberia, steppe; MS – Middle Siberia, Southern taiga; FEn – Äàëüíèé Âîñòîê, ñåâåðíàÿ òàéãà; FEs – Far East, Primorie; Ch – Northeast China and Mongolia; Jap – Japanese islands.

$adjR^2 = 0.854.$ (3)

Variable ($1/D$) introduced in the structure of the model (3) for correction of allometry, biased in small trees due to the shift of diameter D in the upper part of tree crown, and variable (D) - for correction of allometry, suspended at large, old-aged trees.

Tabulating of built additive models (2) in Excel format is fulfilled. Because the volume of tables obtained can exceed the format of journal article, we are limit ourselves to some regional characteristics analysis of the structure of biomass of trees of the same size when using the fragment of summary table for birch (Table 3). Their analysis shows that the maximum values of total biomass of equal size trees occur in Western and Central Europe (97 kg) and in the eastern part of the birch areal - in Primorye, Northeast China, Japan (80-98 kg), that are under the influence of a humid climate of the Atlantic and Pacific oceans, accordingly. Lowest indices (62-70 kg) fall on Ural-Siberian region and the northern territory of the Far East (Magadan Oblast), characterized by a pronounced continental climate.

It was found (Cunia and Briggs, 1984; Reed and Green, 1985), that the correction of internal inconsistency of biomass equations by ensuring their additivity does not necessarily means improvements in the accuracy of biomass estimating, it is necessary to ascertain, whether adequate the additive model obtained and how its adequacy characteristics are related to the same indices of independent (trivial) equations?

To this purpose, the estimates of biomass obtained from independent and additive equations are compared with actual biomass values by calculating the coefficient of determination R^2 calculated by the formula;

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(Y_i - \bar{Y}_i)^2}{\sum_{i=1}^{N}(Y_i - \bar{Y}_i)^2} \quad .. (4)$$

where Y_i - actual biomass values; - predicted biomass values; - the mean actual value of all (N)

Table 2. Three-step additive model of component biomass composition for birch trees, obtained by proportional weighing.

$Pt = 0.3509\, D^{1.7784} H^{-0.1937} D^{0.2073(\ln H)} e^{-0.2349X1} e^{-0.3636X2} e^{-0.3496X3} e^{-0.3294X4} e^{-0.4561X5} e^{-0.0021X6} e^{0.0041X7} e^{-0.2068X8} e^{-0.}$	
Step 1	$Pa = \frac{1}{1+1.2722\, D^{1.5061} H^{-1.5766} D^{-0.1568(\ln H)} e^{-0.3050X1} e^{-0.8973X2} e^{-0.7181X3} e^{-0.5657X4} e^{-1.3714X5} e^{-0.8117X6} e^{-1.0045X7} e^{-1.3660X8} e^{-0.8219X9} e^{-0.4229X10}} \times Pt$
	$Pr = \frac{1}{1+0.7860\, D^{-1.5061} H^{1.5766} D^{0.1568(\ln H)} e^{0.3050X1} e^{0.8973X2} e^{0.7181X3} e^{0.5657X4} e^{1.3714X5} e^{0.8117X6} e^{1.0045X7} e^{1.3660X8} e^{0.8219X9} e^{0.4229X10}} \times Pt$
Step 2	$Pc = \frac{1}{1+0.5769\, D^{-0.0626} H^{1.3493} D^{-0.2106(\ln H)} e^{0.1556X1} e^{0.5260X2} e^{0.0799X3} e^{0.0248X4} e^{-0.6813X5} e^{0.2219X6} e^{-0.3504X7} e^{0.3394X8} e^{0.1840X9} e^{-0.0087X10}} \times Pa$
	$Ps = \frac{1}{1+1.7333\, D^{0.0626} H^{-1.3493} D^{0.2106(\ln H)} e^{-0.1556X1} e^{-0.5260X2} e^{-0.0799X3} e^{-0.0248X4} e^{0.6813X5} e^{-0.2219X6} e^{0.3504X7} e^{-0.3394X8} e^{-0.1840X9} e^{0.0087X10}} \times Pa$
Step 3*a*	$Pf = \frac{1}{1+2.9390\, D^{0.0616} H^{-0.0864} D^{0.1620(\ln H)} e^{-0.8698X1} e^{-0.7495X2} e^{-0.8226X3} e^{-0.8148X4} e^{-0.4328X5} e^{-0.1450X6} e^{-0.0239X7} e^{0.1260X8} e^{-0.5794X9} e^{-0.1047X10}} \times Pc$
	$Pb = \frac{1}{1+0.3402\, D^{-0.0616} H^{0.0864} D^{-0.1620(\ln H)} e^{0.8698X1} e^{0.7495X2} e^{0.8226X3} e^{0.8148X4} e^{0.4328X5} e^{0.1450X6} e^{0.0239X7} e^{-0.1260X8} e^{0.5794X9} e^{0.1047X10}} \times Pc$
Step 3*b*	$Pw = \frac{1}{1+0.5496\, D^{0.0743} H^{-0.6718} D^{0.0819(\ln H)} e^{-0.0587X1} e^{-0.2409X2} e^{0.1638X3} e^{-0.2220X4} e^{-0.5014X5} e^{-0.3071X6} e^{-0.5162X7} e^{-0.0510X8} e^{0.1605X9} e^{-0.1407X10}} \times Ps$
	$Pbk = \frac{1}{1+1.8196\, D^{-0.0743} H^{0.6718} D^{-0.0819(\ln H)} e^{0.0587X1} e^{0.2409X2} e^{-0.1638X3} e^{0.2220X4} e^{0.5014X5} e^{0.3071X6} e^{0.5162X7} e^{0.0510X8} e^{-0.1605X9} e^{0.1407X10}} \times Ps$

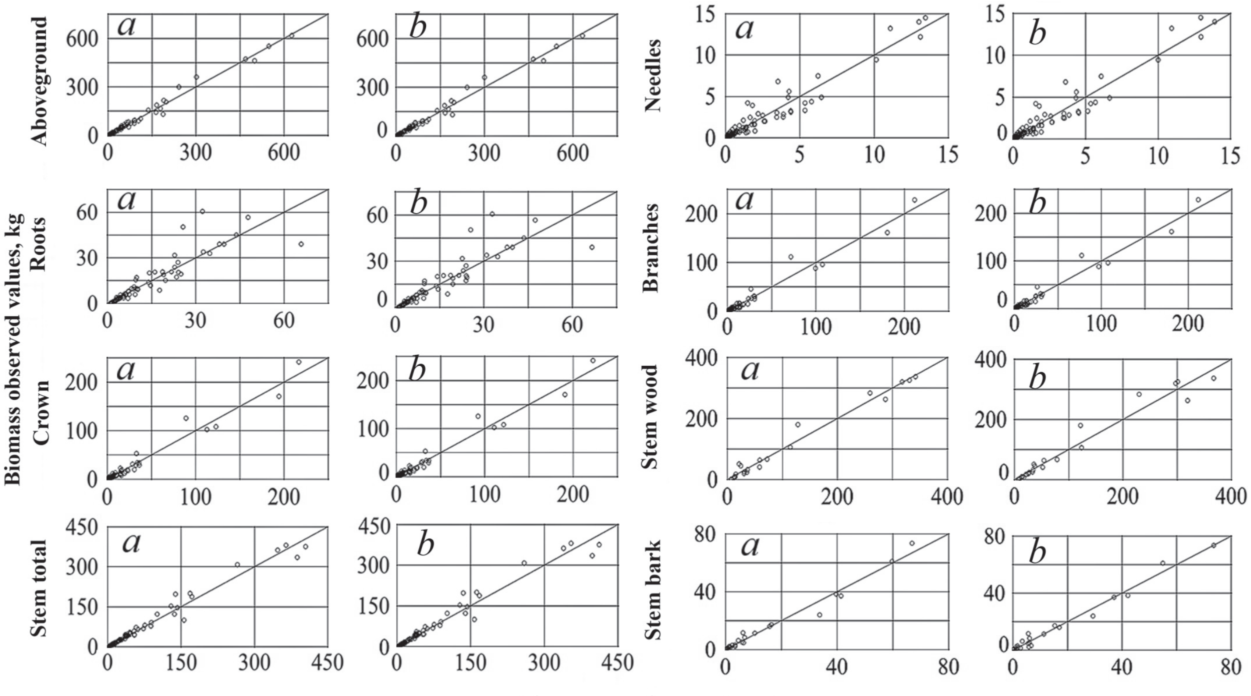

Fig.1. The ratio of observed values and the values derived by calculation of independent (*a*) and additive (*b*) models of tree biomass.

trees.

The results of the comparison indicate that while additive equations internally consistent, but compared to the independent equations they have better characteristics of adequacy not for all component biomass. As already has been noted, when implementing the additivity principle, the aim of improving adequacy of the models obtained in comparison to the traditional models was not provided. The ratio of actual values and derived ones by tabulating independent and additive tree biomass models (Fig. 1) shows the degree of correlativeness of the actual and calculated values and, in many cases, the absence of visible differences in the structure of residual variances obtained on two mentioned models. More or less the value of R^2 of one or the other model is determined by the random position of actual values of biomass of largest trees in confidence belt and uneven dispersion, namely accidental because of their small

Table 3. Fragments of the table of additive tree biomass for diameter 14 cm and tree height of 14 m according to the eco-regions and corresponding species of the genus *Betula.*

Biomass component	Eco-regions and corresponding species of the genus *Betula*										
	WMÅ *B. alba*	ÅR*B.* *alba*	Ural *B. alba*	WSst *B. alba*	MS *B. alba*	FEn *B.* *platyphylla*	FEs *B.* *platyphylla*	FEs *B.* *costata*	FEs*B.* *dahurica*	Ch*B.* *platy-phylla*	Jap *B.* *platy phylla*
Total	97.42	77.03	67.73	68.68	70.08	61.74	97.22	97.82	79.22	82.37	79.54
Roots	25.48	15.95	8.55	10.12	11.74	5.09	13.21	11.23	6.57	11.10	14.98
Aboveground	71.94	61.08	59.18	58.56	58.34	56.65	84.00	86.59	72.65	71.27	64.55
Tree crown	14.47	10.83	7.67	11.05	11.51	18.83	14.10	22.81	11.05	12.35	13.08
Foliage	1.52	2.37	1.53	2.33	2.41	2.89	1.69	2.45	1.04	2.14	1.51
Branches	12.95	8.46	6.14	8.72	9.09	15.94	12.41	20.36	10.01	10.21	11.57
Stem total	57.47	50.25	51.51	47.51	46.83	37.82	69.90	63.78	61.60	58.92	51.48
Stem wood	47.86	42.25	44.49	38.43	40.35	33.72	60.90	56.96	51.73	47.68	43.83
Stem bark	9.61	8.00	7.02	9.09	6.49	4.10	9.00	6.82	9.87	11.24	7.65

number and the greatest contribution to the residual variance (see Figure 1).

CONCLUSIONS

Thus, when using the unique in terms of the volume of database on the level of a single-tree of the genus *Betula* sp., the trans-Eurasian additive allometric model of biomass of trees for Eurasian birch forests is developed for the first time, and thereby the combined problem of model additivity and generality is solved. The additive model of tree biomass of *Betula* sp. is harmonized in two ways: it eliminated the internal contradictions of the component and the total biomass equations, and in addition, it takes into account regional differences of trees of equal sizes not only on total, aboveground and underground biomass, but also on its component structure, i.e. it reflects the regional peculiarities of the component structure of tree biomass. The proposed model and corresponding tables for estimating tree biomass makes them possible to calculate birch stand biomass (t/ha) on Eurasian forests when using measuring taxation.

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