The Investigation of the Additive Allometric Models of Biomass

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Abstract

When using the unique in terms of the volumes of databases on the level of a stand of Picea and Abies spp., the trans-Eurasian additive allometric models of biomass for Eurasian forests are developed for the first time, and thereby the combined problem of model additivity and generality is solved. The additive model of forest biomass of Picea and Abies is harmonized in three levels, one of which provides the principle of additivity of biomass components, the second one is associated with the introduction of dummy independent variables localizing model for eco-regions of Eurasia, and the third one makes the biomass structure of spruce and fir compatible by means of binary variable. The model can be developed further according to the third level of harmonization, when instead of the binary variable one can include another block of dummy variables coding the membership of actual biomass data of each eco-region to basic forest-forming wood species in Eurasia. This might be a subject for further research.

Introduction

In recent years, the scientific branch associated with the estimating the biological productivity of trees and stands is the most intensely developed in two aspects: (1) in compiling the world's actual data bases on biological productivity at the levels of forest stands and sample trees with their development through global and transcontinental patterns [47,29,28,8,25, 21,4] and (2) in the development of methodological bases of regression modeling with the aim to improve the accuracy of our estimates and the correctness of the empirical models of biological productivity of forests and their constituent trees.

The development of generic allometric biomass models [35,30,7,24,53,6,48,26,32] is replaced by the phasing out of them and moving on to the concept of their harmonizing in terms of component composition.

Harmonization implies at least two directions: (1) designing of compatible regional models based on dummy variables [40,36,38,47,10,22,20,50,49,15,33,19,52,16,18,17,51,42,43,44] and (2) designing of compatible models based on the principles of additivity of biomass component composition [23,5,3,2,9,31,13,12,14,31,42,46].

Additive biomass models usually are designed on the tree level, but on the stand level they are presented today with single studies [1,11,42,46,45) without any attempts of their regionalization. In our study, the first attempt of combined solution the problem of additivity and universality of biomass allometric models of forest stands on the examples of the genera of *Picea* sp. and *Abies* sp.

Methodology

As a basis for designing models, the database of forest biomass of woody species in Eurasia is used [41,37] from which the materials in a number of 925 sample plots, including 670 plots for pure spruce stands and mixed with fir and 255 plots for pure fir stands and mixed with spruce are taken. Those and other are distributed across eight eco-regions and marked respectively with eight dummy variables from X_0 to X_7.

Results and Discussion

The procedure of modelling involves several stages. At the first stage initial (original) allometric equations are calculated in the following order: for total biomass, then for the aboveground biomass (intermediate component of the 1-th order) and for the roots, then for intermediate components of the 2nd order, i.e. for crown and stems with bark, and, finally, for the original components, i.e. firstly for needles and branches and secondly for stem wood and stem bark, according to their structure taken into account:

$$\ln P_i = a_i + b_i(\ln A) + c_i(\ln A)^2 + d_i(\ln H) + e_i(\ln D) + f_i(\ln N) + g_i Y_k + \Sigma h_{ij} X_j, \quad (1)$$

where P_i is biomass of *i*-th component, t per ha; *A* is stand age, yrs; *H* is the mean height of a stand, m; *D* is the mean diameter at breast height, cm; *N* is tree density, thousand trees per ha; *a-h* are regression coefficients; *i* is designation of biomass component: total (*t*), aboveground (*a*), roots (*r*), crown (*c*), stems above bark (*s*), needles (*f*), branches (*b*), stem wood (*w*) and stem bark (*bk*); Y_k is binary variable: for spruce $k = 1$, for fir $k = 0$; *j* are the codes of dummy variables for ecoregions designation, from 0 to 7. After the anti-log transformation the model (1) has the form

$$P_i = a_i A^{bi} A^{ci(\ln A)} H^{di} D^{ei} N^{fi} e^{giYk} e^{\Sigma hijXj} \quad (2)$$

Approximation of the model (1) on actual biomass data gives the regression coefficients and indices of adequacy. All regression coefficients of numerical variables are significant at the level of probability $P_{0.95}$, and the equations are adequate to original data.

At the second stage of the study, the structure of the additive model and its calculating algorithm proposed by Chinese researchers [34,12] are modified in accordance with the specifics of our study, and the result obtained in the form of additive and regionally distributed model of triple harmonization is shown in the **Table 1**. The model is valid in the range of actual data of stand age, mean height, mean diameter and tree density and is characterized by the triple harmonization: one of which provides the principle of additivity of biomass components, the second one is related to the introduction of dummy variables that localizing model for eco-region of Eurasia and the third one conforms (harmonizes) the biomass structure of spruce and fir through the binary variable.

Table 1: Additive model of spruce and fir biomass, calculated according to the principle of three-step proportional weighting.

$$P_t = 0.3902\, A^{0.4178} A^{-0.0400(\ln A)} H^{0.8226}\, D^{0.9835}\, N^{0.5509}\, e^{-0.0530Yk}\, e^{-0.1868X1}\, e^{-0.1756X2}\, e^{-0.5337X3}\, e^{-0.4969X4}\, e^{-0.3584X5}\, e^{0.1492X6}\, e^{0.7970X7}$$

Step 1	$P_a =$	$\dfrac{1}{1+ 1.1054\, A^{-0.8767}\, A^{0.1248(\ln A)}\, H^{-0.1950}\, D^{0.1542}\, N^{-0.0150}\, e^{0.0879Yk}\, e^{-0.0266X1}\, e^{0.3958X2}\, e^{-1.2227X3}\, e^{-0.1038X4}\, e^{-0.1180X5}\, e^{0.1815X6}\, e^{-0.2651X7}}$	$\times\, Pt$
	$P_r =$	$\dfrac{1}{1+ 0.9047\, A^{0.8767}\, A^{-0.1248(\ln A)}\, H^{0.1950}\, D^{-0.1542}\, N^{0.0150}\, e^{-0.0879Yk}\, e^{0.0266X1}\, e^{-0.3958X2}\, e^{1.2227X3}\, e^{0.1038X4}\, e^{0.1180X5}\, e^{-0.1815X6}\, e^{0.2651X7}}$	$\times\, Pt$
Step 2	$P_c =$	$\dfrac{1}{1+ 0.0153\, A^{1.4669}\, A^{-0.1482(\ln A)}\, H^{0.6711}\, D^{0.0272}\, N^{0.1150}\, e^{-0.1238Yk}\, e^{0.2254X1}\, e^{0.0571X2}\, e^{0.0400X3}\, e^{0.0276X4}\, e^{0.0251X5}\, e^{0.1764X6}\, e^{0.5181X7}}$	$\times\, Pa$
	$P_s =$	$\dfrac{1}{1+ 65.4793\, A^{-1.4669} A^{0.1482(\ln A)}\, H^{-0.6711}\, D^{-0.0272}\, N^{-0.1150}\, e^{0.1238Yk}\, e^{-0.2254X1}\, e^{-0.0571X2}\, e^{-0.0400X3}\, e^{-0.0276X4}\, e^{-0.0251X5}\, e^{-0.1764X6}\, e^{-0.5181X7}}$	$\times\, Pa$
Step 3a	$P_f =$	$\dfrac{1}{1+ 0.6859\, A^{-0.1280}\, A^{0.0335(\ln A)}\, H^{-0.3037}\, D^{0.5125}\, N^{-0.0077}\, e^{0.1155Yk}\, e^{0.0730X1}\, e^{-0.0709X2}\, e^{0.0602X3}\, e^{0.1102X4}\, e^{0.2717X5}\, e^{-0.1208X6}\, e^{0.3092X7}}$	$\times\, Pc$
	$P_b =$	$\dfrac{1}{1+ 1.4579\, A^{0.1280}\, A^{-0.0335(\ln A)}\, H^{0.3037}\, D^{-0.5125}\, N^{-0.0077}\, e^{-0.1155Yk}\, e^{-0.0730X1}\, e^{0.0709X2}\, e^{-0.0602X3}\, e^{-0.1102X4}\, e^{-0.2717X5}\, e^{0.1208X6}\, e^{-0.3092X7}}$	$\times\, Pc$
Step 3б	$P_w =$	$\dfrac{1}{1+ 1.0857\, A^{-0.6355}\, A^{0.0872(\ln A)}\, H^{-0.0032}\, D^{-0.3688}\, N^{-0.0036}\, e^{-0.1533Yk}\, e^{-0.1216X1}\, e^{0.0596X2}\, e^{0.1234X3}\, e^{0.2260X4}\, e^{0.2934X5}\, e^{0.2008X6}\, e^{0.1048X7}}$	$\times\, Ps$
	$P_{bk} =$	$\dfrac{1}{1+ 0.9211\, A^{0.6355}\, A^{-0.0872(\ln A)}\, H^{0.0032}\, D^{0.3688}\, N^{0.0036}\, e^{0.1533Yk}\, e^{0.1216X1}\, e^{-0.0596X2}\, e^{-0.1234X3}\, e^{-0.2260X4}\, e^{-0.2934X5}\, e^{-0.2008X6}\, e^{-0.1048X7}}$	$\times\, Ps$

At the third stage of the study the adequacy comparison between the additive model (Table 1) and the initial (original) equations (1). As an additive model and initial equations (1) are tabulated on actual biomass-forming indices and the calculated biomass values were compared with the actual ones using the formulas:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(Y_i - \hat{Y}_i)^2}{\sum_{i=1}^{N}(Y_i - \bar{Y}_i)^2} \qquad RMSE = \sqrt{\frac{\sum_{i=1}^{N}(Y_i - \hat{Y}_i)^2}{N-p}}, \quad (3)$$

where Y_i - actual value; $\hat{Y}_i$ - calculated value according to the model; $\bar{Y}$ - mean actual value of the all (N) plots; $p = 5$ – number of variables; N – total plot number, involving into calculating R^2 and *RMSE*.

The results of comparison of the adequacy of two modeling methods are summarized in the Table 2, indicating higher adequacy of additive model compared to the original (non-additive) equations.

Table 2: Comparison of indices of the adequacy of the initial and additive biomass equations of spruce and fir stands, calculated with their regionalization by dummy variables.

Indices	Biomass components*								
	P_t	P_a	P_r	P_s	P_w	P_{bk}	P_c	P_b	P_f
Initial equations									
R^2	0,842	0,809	0,625	0,781	0,741	0,359	0,549	0,513	0,452
RMSE	52,44	47,35	17,10	43,17	41,43	7,32	13,04	9,38	5,65
Additive equations									
R^2	0,842	0,845	0,625	0,848	0,827	0,446	0,574	0,561	0,461
RMSE	52,44	42,60	17,10	35,95	33,85	6,81	12,68	8,91	5,60

* Designations see equation (1).

The additive model designed (Table 1) includes four numeric independent variables. When its tabulating, the problem occurs, which is that we can give (know) of four independent variables (*A, D, H, N*) only stand age, and the remaining three variables can be entered into the table in the form of calculated values, obtained by using the system of auxiliary recursive equations [46]. Such equations are designed using the original database and are shown in the **Table 3**.

The results of sequential tabulation of equations 3 and 1 are the rather cumbersome table, the volume of which exceeds the format of a journal article. Therefore, a comparative analysis of the biomass structures of spruce and fir stands of different ecoregions we limit with the age 60 years (**Table 4**). According to the Table 4, the highest biomass values correspond to the regions with minimal index of continentality, adjacent to the Atlantic and Pacific coasts, and the lowest values to the regions of Siberia, with its maximum index of continentality.

Table 3: Characteristics of recursive auxiliary equations for biomass-forming indices.

Indices	Regression coefficients												$adjR^2$*	*SE**
H	-12.064	8.1935 ln*A*	-	-	-0.7705*Yk*	-5.5591*X1*	-7.3551*X2*	0.2640*X3*	-7.5885*X4*	-7.2617*X5*	-9.8684*X6*	-9.8245*X7*	0.588	5.12
ln*D*	-0.2084	0.1838 ln*A*	0.8559 ln*H*	-	-0.0217*Yk*	-0.0946*X1*	-0.0607*X2*	0.2524*X3*	-0.0374*X4*	0.0050*X5*	0.1469*X6*	0.2757*X7*	0.920	0,19
ln*N*	4.0504	-0.0731 ln*A*	0.5408 ln*H*	-1.7132 ln*D*	0.0493*Yk*	-0.1011*X1*	-0.3848*X2*	0.5868*X3*	-0.3040*X4*	0.5776*X5*	0.5769*X6*	-0.2256*X7*	0.759	0.48

Table 4: Fragment of additive transcontinental table of spruce and fir biomass stands for the age of 60 years, localized on the ecoregions of Eurasia.

Ecoregion	Species	*H*, m	*D*, cv	*N*, 1000 trees /ha	Biomass , t per ha*								
					P_t	P_a	P_c	P_f	P_b	P_r	P_s	P_w	P_{bk}
Picea Dietr. stands													
WME	*P. abies, P. sitchensis*	20,7	22,6	1,106	287,0	231,3	48,1	19,7	28,4	55,6	183,2	167,6	15,7
EPR	*P. abies, P. obovata*	15,2	15,7	1,569	156,4	126,7	27,0	11,1	15,9	29,7	99,7	91,1	8,6
Ural	*P. abies, P. obovata*	13,4	14,6	1,253	117,1	93,4	27,2	13,2	13,9	23,7	66,3	59,3	6,9
Cau	*P. orientalis*	21,0	29,4	1,275	238,3	219,6	50,3	15,9	34,4	18,7	169,4	154,5	14,8
MES	*P. obovata*	13,1	14,7	1,327	87,1	70,2	18,6	7,7	10,9	16,8	51,7	45,4	6,2
FE	*P. jezoensis*	13,5	15,7	2,912	167,5	138,5	35,4	11,8	23,6	29,0	103,1	90,2	12,9
Japan	*P. koraiensis, P. glehnii*	10,8	15,0	2,786	218,1	166,6	42,4	16,9	25,4	51,5	124,3	109,7	14,5
China	*P. purpurea*	10,9	17,1	0,998	270,6	215,6	61,2	23,3	37,8	55,0	154,4	138,5	15,9
Abies Mill. stands													
WME	*A. alba*	21,5	23,8	0,980	307,4	254,8	47,9	20,9	27,1	52,6	206,9	186,9	20,0
EPR	*A. sibirica*	15,9	16,8	1,375	170,1	141,6	27,2	11,8	15,4	28,4	114,4	103,3	11,1
Ural	*A. sibirica*	14,1	15,6	1,091	128,3	105,4	27,8	14,3	13,5	22,9	77,6	68,5	9,1
Cau	*A. nordmanniana*	21,7	30,9	1,131	255,2	237,8	49,4	16,7	32,6	17,4	188,4	169,8	18,6
MES	*A. sibirica*	13,9	15,8	1,154	95,5	79,2	18,9	8,3	10,6	16,3	60,3	52,2	8,1
FE	*A. nephrolepis*	14,2	16,8	2,537	183,5	155,5	35,9	12,8	23,1	27,9	119,6	102,9	16,7
Japan	*A. sachalinensis, A. veitchii, A. firma*	11,6	16,3	2,398	242,5	191,8	43,9	18,6	25,2	50,7	147,9	128,6	19,3
China	*Cunninghamia lanceolata*	11,7	18,6	0,859	300,7	246,9	63,2	25,7	37,5	53,9	183,6	162,5	21,2

* Denotes of the ecoregions: WME – Western and Middle Europe; EPR – European part of Russia; Ural – Ural region; Cau – Caucasus; MES – Middle and Eastern Siberia; FE – Far Eastern province (Primorye).

Negative correlation of calculated indices of spruce and fir biomass with continentality index by [48,4,27) is characterized by a correlation coefficient -0.92 to total phytomass and -0.89 for aboveground ones on the probability level above P_{95}.

Conclusion

Thus, for the first time, when using the unique in terms of volume database on the examples of the genera *Picea* sp. and *Abies* sp. the comparative analysis of biomass structure of forest stands on the territory of Eurasia is fulfilled in a new light, the result of which is the additive allometric model, harmonized on three levels, one of which provides the principle of additivity of biomass components, the second one relates to the involving dummy variables, localizing the model along to ecoregions of Eurasia, and the third one harmonizes the structure of a transcontinental model of spruce and fir stands by involving the binary variable into biomass model. It is shown that the model demonstrates differences between spruce and fir stand biomass not only for its absolute values for stem, needles, branches and roots (as is typical for trivial independent models that includes only dummy variables), but also for their ratios, i.e. the differences in the biomass structure.

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