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# ABOVEGROUND BIOMASS OF MONGOLIAN LARCH (*LARIX SIBIRICA* LEDEB.) FORESTS IN THE EURASIAN REGION

**ABSTRACT.** We used our database of tree biomass with a number of 433 sample trees of *Larix* from different ecoregions of Eurasia, involving 61 trees from Mongolia for developing an additive model of biomass tree components. Our approach solved the combined problem of additivity and regionality of the model. Our additive model of tree aboveground biomass was harmonized in two ways: first, it eliminated the internal contradictions of the component and of the total biomass equations, secondly, it took into account regional (and correspondingly species-specific) differences of trees in its component structure. A significant excess of larch biomass in the forest-tundra is found that may be explained by permafrost conditions, by tree growth in low-yielding stands with a high basic density of stem wood and relatively high developed tree crown in open stands. The aboveground biomass of larch trees in Mongolia does not stand out against the background of the most ecoregions of Eurasia. Based on our results, we conclude that the growing conditions of larch in Mongolia are not as tough as it was suggested earlier by other scientists. Biomass relations between regions may be explained by unknown and unaccounted factors and errors of measurements in all their phases (assessment of age, diameter, height of a tree, the selection of supposedly representative samples of component biomass, their drying, weighing, etc.). The question what explains the regional differences in the structure of biomass of trees with the same linear dimensions of their stems, remains open. Undoubtedly, the differences in tree age here play an important role. Also, important factor is the variation in the morphological structure of stands, which, in turn, is determined by both climatic and edaphic factors. The obtained models allow the determination of larch forest biomass in different ecoregions of Eurasia with the help of height and diameter data.

**KEY WORDS:** genus *Larix* spp., aboveground tree biomass, regional differences, equations additivity, allometric models, dummy variables, tables of biomass.

**CITATION:** Vladimir A. Usoltsev, Igor M. Danilin, Zaandrabalyn Tsogt, Anna A. Osmirko, Ivan S. Tsepordey, Viktor P. Chasovskikh (2019) Aboveground Biomass Of Mongolian Larch (*Larix Sibirica* Ledeb.) Forests In The Eurasian Region. Geography, Environment, Sustainability, Vol.12, No 3, p. 117-132  
DOI-10.24057/2071-9388-2018-70

## INTRODUCTION

Forest ecosystems play an important role as sinks of atmospheric carbon. Since a significant part of forest cover has been represented by mixed forests, for the correct estimation of their biological productivity in many cases allometric models of biomass are needed, developed at a tree level. The regression (allometric) method of estimating forest biomass when using the results of sampling of model trees, was represented in the whole range of stem diameters (and sometimes of tree height) is the current standard (Marklund 1983). In conditions of continuously increasing biosphere function of forest cover of the planet, there is a trend related to the harmonization of allometric models of tree biomass, that is fulfilled either by involving dummy variables into a model (Jacobs and Cunia 1980; Fu et al. 2012; Zeng 2015), or by providing additive component composition (Kozak 1970; Parresol 2001; Zheng et al. 2015; Zhang et al. 2016). The additivity of the component composition assumes the consistency of the model by biomass components and means that the total biomass of components (stems, branches, needles) obtained by the component equations is equal to the value of biomass obtained by the equation for total biomass. According to Sanquetta et al. (2015), independent (without additivity) fitting of coefficients for biomass components and total biomass is not satisfactory, but this is not observed in case when the simultaneous fitting is used, accounting the additivity principle and resulting in more effective estimators.

These and other models are usually developed on local (regional) harvest data of tree biomass. As a result, the published models have either regional application

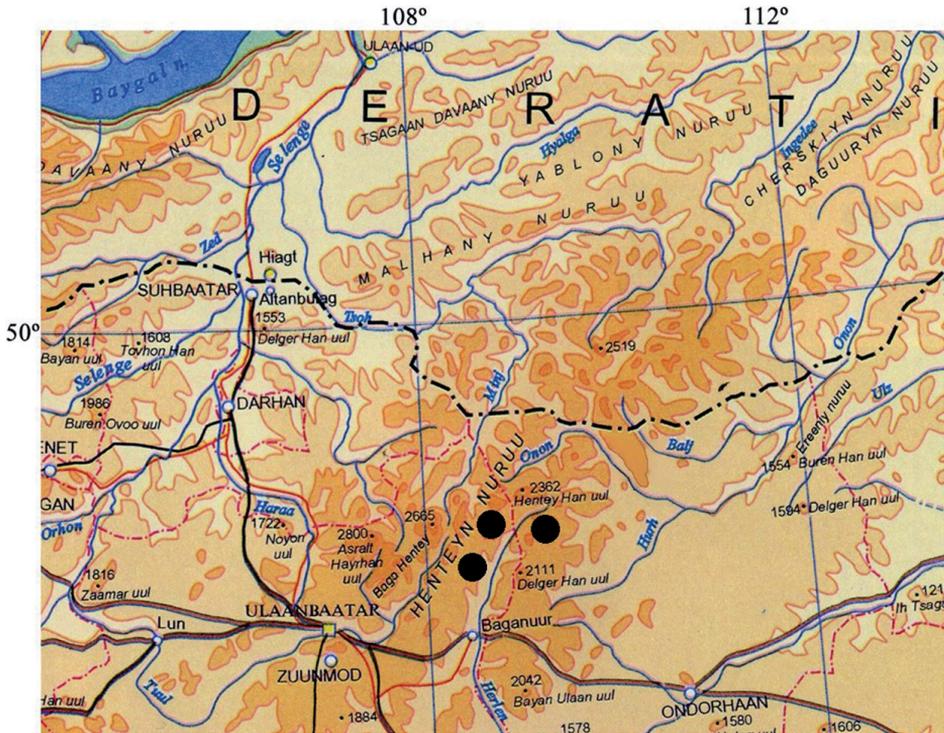
without harmonization with the help of dummy variables and without providing the principle of component additivity composition, or provide additivity of component composition but without any regionalization (Usoltsev 2017). For genus *Larix* spp. a number of models for estimating the aboveground biomass from stem diameter and height data have already been published (Shi et al. 2002; Bjarnadottir et al. 2007; Novák et al. 2011; Zhao et al. 2011; Battulga et al. 2013), but they are of regional nature and do not ensure the additivity of the component composition of the biomass.

The goal of this paper to be combine the mentioned approaches, and to develop a regional additive model (AM) of tree aboveground biomass on the example of the Siberian larch in Mongolia, interfaced with the tree biomass of other regions of Eurasia by involving dummy variables (Draper and Smith 1966) into a model.

## MATERIALS AND METHODS

The database of single-tree biomass created for the forest-forming species of Eurasia provides the data to develop the called modern methodological developments on the trans-continental level (Usoltsev 2016). Harvest data on the biomass of 43 trees were obtained in the forests of the Siberian larch (*Larix sibirica* Ledeb.) of north-eastern Mongolia, the Eastern part of Khentii Mountains, near the village of Mungun-Mort (49°10'N, 110°0'E, 700-1500 m a.s.l.) (Fig. 1).

We established 5 sample plots and measured all trees. Each plot considers an area involving 200-400 trees with the height more 1.5 m and stem diameter at breast height (DBH) more 0.5 cm. Range of diameter classes varies from 0.5 to 32



**Fig. 1. The position of the sample area on the map of Khentii Mountains (marked by the black points). Scale 1: 6000000**

cm. On each plot we harvested model trees – one mean value exemplar of each DBH class. Model trees were completely divided into biomass components and weighed in wet state at lever arid balance with an accuracy to  $\pm 1$  g at a weight up to 10 kg and with an accuracy to  $\pm 100$  g at a weight greater than 10 kg. Samples from each component were packed into polyethylene packets, marked, and transported to the laboratory, where to determine moisture content they were dried in a dryer up to an absolutely dry state ( $+105^{\circ}\text{C}$  during three days) and weighed at electronic scale with an accuracy to  $\pm 0.1$  g. The weight of components in an absolutely dry state was equalized analytically, summed according to classes of stem thickness, and reduced to 1 hectare. Bark wood ratio was found from samples cut out of the stem at different heights (according to sections). The length of sections was determined depending on the height of the tree stem. The number of sections for each tree was no less than 10. The calculation of the stem volume

was performed according to the complex Huber's formula (Danilin 2009; Danilin and Tsogt 2014, 2015). The results of estimating the tree biomass on the sample plots are shown in Table 1. We draw attention to the relatively high density of larch stands, that is typical for larch, growing not only in the harsh mountainous areas of Mongolia, but also in the northern taiga of Russia. In particular, larch has 112 thousand trees per 1 ha at the age of 14 years in Yakutia ( $62^{\circ}\text{N}$ ,  $130^{\circ}\text{E}$ ) (Pozdnyakov 1975), 55 thousand trees per 1 ha at the age of 30 years in the upper Kolyma river ( $62^{\circ}\text{N}$ ,  $147^{\circ}\text{E}$ ) (Pozdnyakov 1975), 4.8 thousand per ha at the age of 40 years near Arkhangelsk ( $64^{\circ}\text{N}$ ,  $40^{\circ}\text{E}$ ) (Molchanov 1971), 2.7-2.9 thousand per ha at the age of 86-87 years in the basin of the Nizhnyaya Tunguska river ( $64^{\circ}\text{N}$ ,  $100^{\circ}\text{E}$ ) (Abaimov et al. 1997).

In another region of Mongolia, on its western border in the mountains of the Mongolian Altai, the biomass structure of Siberian larch trees was studied on 18 sample plots, and allometric models of

**Table 1. Aboveground biomass of larch trees in the eastern part of the Khentii Mountains**

No.	Tree age, years	Stem DBH, cm	Tree height, m	Stem volume, dm <sup>3</sup>		Biomass in absolutely dry condition, kg					Tree numbers per ha	Mean diameter, cm
				Total	Stem bark	Stem		Branches	Foliage	Sum total		
						Total	Bark only					
1	18	8.9	6.5	22.6	7.1	9.6	2.3	6.2	2.6	18.4	56200	1.6
2	18	7.5	5.9	16.9	5.3	7.4	1.8	4.6	1.9	13.9		
3	18	6.3	5.2	11.2	3.5	5.1	1.3	2.7	1.1	8.9		
4	17	4.9	4.9	6.4	2.0	3.1	0.8	1.2	0.7	5.0		
5	18	4.0	4.3	4.3	1.4	2.0	0.6	0.84	0.5	3.34		
6	17	2.9	3.6	2.2	0.9	1.0	0.3	0.42	0.3	1.72		
7	15	1.9	3.3	1.1	0.5	0.4	0.1	0.21	0.1	0.62		
8	14	1.0	2.4	0.2	0.05	0.12	0.05	0.032	0.03	0.182		
9	15	0.5	1.5	0.1	0.05	0.05	0.02	0.021	0.01	0.081		
10	32	17.6	11.3	125.4	37.9	51.4	11.2	19.8	7.5	78.7	5700	5.9
11	35	15.4	11.1	100.6	28.1	40.2	8.8	13.8	5.2	59.2		
12	36	13.2	10.7	75.8	18.4	29.0	6.4	8.0	2.9	39.9		
13	27	9.8	8.3	39.9	9.5	18.4	4.8	8.1	2.7	29.2		
14	27	7.3	7.3	18.3	5.4	8.5	2.3	3.3	1.3	13.1		
15	25	3.9	5.8	4.3	1.2	1.9	0.6	0.5	0.2	2.6		
16	21	1.8	3.0	0.8	0.3	0.4	0.1	0.21	0.04	0.65		
17	15	0.8	2.3	0.2	0.1	0.15	0.05	0.04	0.01	0.20		
18	33	12.5	10.9	73.8	20.8	29.7	6.7	3.7	1.4	34.8		
19	34	11.2	10.4	54.4	16.8	23.5	3.7	3.4	0.9	27.8		
20	32	10.1	10.0	43.9	13.4	19.0	3.6	2.8	0.7	22.5		
21	30	8.8	9.5	33.3	10.0	14.2	3.3	2.1	0.5	16.8		
22	31	8.0	9.2	27.1	8.3	11.5	2.9	1.66	0.44	13.6		
23	35	7.1	8.8	20.8	6.6	8.7	2.4	0.95	0.40	10.05		
24	29	5.6	7.9	10.5	2.2	4.8	1.2	0.23	0.06	5.09		
25	24	4.1	7.1	5.3	0.9	2.7	0.7	0.08	0.03	2.81		
26	27	3.2	6.2	2.9	0.9	1.4	0.4	0.07	0.03	1.5		

27	44	31.0	17.8	618.7	144.0	272.0	38.7	53.2	7.8	333.0	2900	7.5
28	43	27.4	17.6	508.4	114.3	228.9	33.2	36.4	6.2	271.5		
29	39	23.5	17.3	398.0	84.5	185.7	27.7	19.5	4.6	209.8		
30	42	19.8	16.8	288.4	60.5	128.5	20.7	13.8	3.4	145.7		
31	43	15.9	16.2	178.8	36.5	71.2	13.6	7.9	2.2	81.3		
32	41	12.0	12.6	102.4	21.6	40.8	8.1	4.7	1.3	46.8		
33	40	8.1	9.0	25.9	6.7	10.3	2.5	1.4	0.6	12.3		
34	33	4.5	6.6	15.8	4.1	3.1	0.7	1.0	0.5	4.6		
35	75	32.3	20.4	662.4	118.7	273.2	56.2	31.2	7.0	311.4	2100	18.4
36	73	29.7	19.9	587.0	111.6	247.5	49.3	25.8	5.9	279.2		
37	74	27.2	19.3	511.5	104.4	221.6	42.3	20.3	4.8	246.7		
38	73	24.5	18.8	436.0	97.2	195.6	35.2	15.0	3.7	214.3		
39	72	22.0	18.2	360.5	90.0	169.8	28.3	9.6	2.5	181.9		
40	70	18.7	17.5	256.2	66.1	112.6	18.6	5.9	1.7	120.2		
41	70	15.4	16.8	151.9	42.2	55.3	8.9	2.0	0.8	58.1		
42	67	12.2	13.7	92.8	26.2	34.4	5.4	1.6	0.7	36.7		
43	60	8.8	10.5	33.7	10.3	13.5	1.9	1.3	0.6	15.4		

above-ground biomass were calculated according to the diameter and height of the stem (Battulga et al. 2013). We decided to find out whether there are differences in the above-ground tree biomass data of the two mountain regions of Mongolia, and depending on the result obtained we can calculate allometric equations either separately for two regions, or to give one generalized equation.

The harvest tree biomass data of the two regions were obtained in different age ranges: on the Khentii Mountains from 14 to 75 years and on the Mongolian Altai from 55 to 173 years. In order to exclude the influence of age on the comparison result, the tree age was involved into the model as an independent variable, in addition to the stem diameter and height. It is known that allometric equations of different regions have differences not only

in the value of the intercept, but also in the slope of the regression line, i.e. allometric exponent (Battulga et al. 2013). With that said, we coded the harvest data of the two regions by the binary variable and calculated the equation of the following structure:

$$P_a = \exp \left[ a_0 + a_1 \ln A + a_2 \ln D + a_3 \ln H + a_4 (\ln D)(\ln H) + a_5 X + a_6 X(\ln D) + a_7 X(\ln H) \right], \quad (1)$$

where  $P_a$  – aboveground tree biomass in dry condition, kg;  $A$  – tree age, yrs;  $D$  – stem diameter at breast height, cm;  $H$  – tree height, m;  $X$  – the binary variable encoding data belonging to two mountainous regions of Mongolia:  $X=1$  for Khentii and  $X=0$  for Mongolian Altai. According to a geometric interpretation of this result, the constant  $a_5$  characterizes

the difference of the regression intercept values of the two regions on the axis of ordinates,  $a_6$  and  $a_7$ , show the difference in the regression slopes of the two regions via the orthogonal axes of abscissas, respectively along the axes  $D$  and  $H$ . The constant  $a_4$  of the variable  $(\ln D)(\ln H)$  corrects the violation of allometry owing to the shift of  $D$  up the stem for small values of  $H$ , which was shown earlier (Usoltsev et al. 2019).

Calculating regression equations using the standard Statgraphics software showed that only the constants  $a_2$  and  $a_4$  were statistically significant (the value of Student's criterion  $t_{act}$  is 8.2 and 7.8, respectively, that is more than  $t_{05} = 2$ ), and the  $t_{act}$  for the constants  $a_1$ ,  $a_3$ ,  $a_5$ ,  $a_6$  and  $a_7$  are 0.85, 0.54, 0.75, 1.80 and 0.80, respectively, which is less than  $t_{05} = 2$ . This means that there are no statistically significant differences between the regressions of the two regions for the aboveground tree biomass, nor on the values of the intercept or on the slopes for  $D$  and  $H$  regression lines. The resulting equation, common to the mountain environments of Mongolia is obtained:

$$P_a = \exp[-1.4874 + 1.6658 \ln D + 0.1610 (\ln D)(\ln H)], \quad (2)$$

$$R^2 = 0.992, \quad RMSE = 1.18,$$

And in the further comparative transcontinental analysis, *Larix* tree biomass of Mongolia is allocated by one common dummy variable.

For the purpose of comparative analysis of larch biomass of Mongolia in geographical aspect, from the above mentioned database 390 sample trees of six species of the genus *Larix spp.* were additionally taken (respectively *L. decidua* Mill., *L. sukaczewii* N. Dyl., *L. sibirica* L., *L. gmelinii* Rupr., *L. cajanderi* Mayr., and *L. leptolepis* Gord.). The entire quantity of the data for this study is 433 trees, representing eight ecoregions, designated accordingly by eight dummy variables from  $X_0$  to  $X_7$  (Table 2). Sample trees were harvested and processed

in a number from 5 to 10 copies on each sample plot. Then samples were taken from each biomass component to determine the dry matter content (and for wood and bark of stems also to determine the basic density) and after drying the samples at the temperature of 80-100° C, the results were recalculated for the whole tree. The distribution of sample plots in the ecoregions of Eurasia is shown in Fig. 2. In this case we do not consider the biomass of roots, because there is lack of such data, they were determined by researchers not at all sample plots, often without specifying the method of their estimation. The analysis of the world data of underground tree biomass showed that due to the imperfection of methods to estimate fine root biomass, the total underground biomass of trees and stands may be underestimated from two to five times (Usoltsev 2018).

The disaggregation method of two-step proportional weighing based on the principle "from general to particular" is developed as an alternative to the above-mentioned independent (without additivity) fitting approach. It has been implemented in two versions: as a sequential (Zheng et al. 2015) and parallel (Zhang et al. 2016) disaggregating additive systems of equations for aboveground biomass (Fig. 3). According to the structure of the disaggregation model of a two-step additive equation system (Zheng et al. 2015), the aboveground biomass  $P_a$ , estimated by the initial equation, is divided into biomass components estimated by corresponding equations (Table 3).

The coefficients of the regression equations of all two steps are evaluated simultaneously, that ensures the additivity of the biomass of all components (Dong et al. 2015). Since the regression coefficients in the designed model have been calculated on the log-transformed data, a corresponding correction has been introduced in the equations to eliminate the displacements caused by

**Table 2. Aboveground biomass of larch trees in the eastern part of the Khentii Mountains**

Ecoregions	Latitude, North	Longitude, East	Species of the genus <i>Larix</i> spp.	Block of dummy variables							Mean DBH $\pm$ SE (cm) and its range (in the brackets)	Mean tree height $\pm$ SE (m) and its range (in the brackets)	Number of trees	Sources	
				X <sub>1</sub>	X <sub>2</sub>	X <sub>3</sub>	X <sub>4</sub>	X <sub>5</sub>	X <sub>6</sub>	X <sub>7</sub>					
Western and Central Europe	47°00' - 49°19'	09°00' - 16°40'	<i>L. decidua</i> Mill.	0	0	0	0	0	0	0	0	17.6 $\pm$ 11.2 (7.1 $\div$ 47.8)	17.7 $\pm$ 5.5 (9.8 $\div$ 34.0)	19	Burger, 1945; Vyskot, 1982
European part of Russia	55°20' - 57°50'	37°00' - 48°10'	<i>L. sukaczewii</i> N.Dyl.	1	0	0	0	0	0	0	0	8.2 $\pm$ 7.1 (1.0 $\div$ 35.0)	8.9 $\pm$ 5.7 (2.3 $\div$ 28.0)	25	Dylis, Nosova, 1977; Polikarpov, 1962; Karaseva, 2003
Turgay steppe	53°30'	64°30'	<i>L. sukaczewii</i> N.Dyl.	0	1	0	0	0	0	0	0	16.1 $\pm$ 6.2 (6.2 $\div$ 28.0)	14.6 $\pm$ 2.4 (7.9 $\div$ 17.8)	28	Usoltsev, 2016
Western Siberia, the flood plain of the Pur river	64°03' - 67°00'	78°00' - 101°10'	<i>L. sibirica</i> L.; <i>L. gmelinii</i> (Rupr.) Rupr.	0	0	1	0	0	0	0	0	11.5 $\pm$ 7.1 (2.1 $\div$ 38.0)	11.1 $\pm$ 5.0 (2.9 $\div$ 24.8)	116	Danilin et al., 2015; Usoltsev, 2016
Eastern Siberia, forest-tundra	70°00'	135°49'	<i>L. cajanderi</i> Mayr.	0	0	0	1	0	0	0	0	7.6 $\pm$ 4.9 (0.3 $\div$ 22.7)	6.5 $\pm$ 2.8 (1.4 $\div$ 14.8)	66	Shchepashchenko, 2015
Russian Far East, northern taiga	60°30'	148°00'	<i>L. cajanderi</i> Mayr.	0	0	0	0	1	0	0	0	18.3 $\pm$ 11.7 (3.9 $\div$ 52.8)	13.9 $\pm$ 7.0 (2.9 $\div$ 30.0)	45	Moskalyuk, 2015
Mountains of Mongolia	49°10'	110°00'	<i>L. sibirica</i> L.	0	0	0	0	0	1	0	0	12.7 $\pm$ 7.7 (0.5 $\div$ 32.3)	11.3 $\pm$ 5.0 (1.5 $\div$ 24.3)	61	Battulga et al. 2013; Danilin et al., 2015
Japanese Islands	36°30' - 36°50'	138°10' - 139°40'	<i>L. leptolepis</i> Gord.	0	0	0	0	0	0	0	1	15.2 $\pm$ 6.6 (4.0 $\div$ 35.9)	13.2 $\pm$ 5.2 (4.3 $\div$ 26.7)	73	Research Group..., 1964; Karizumi, 1974



Fig. 2. Distribution of the sample plots on the territory of Eurasia, on which larch trees have been harvested. The sample area in the Khenk Mountains is marked with the black square

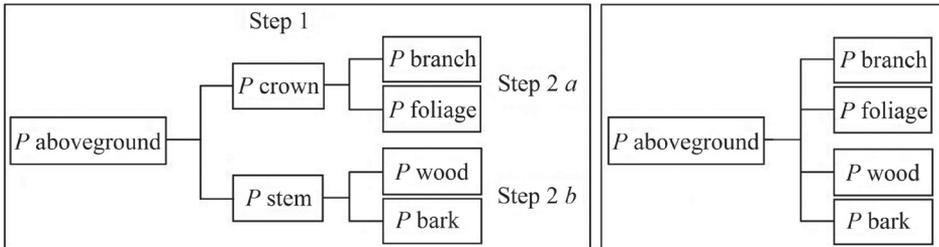


Fig. 3. The pattern of the disaggregating two-step proportional weighting AM of sequential (left) and parallel (right) schemes. The schemes show the relationship between each biomass component, where lines from left to right indicate disaggregation and from right to left indicate summation (Zheng et al. 2015; Zhang et al., 2016)

Table 3. Structure of the two-step additive model (AM), implemented according to the principle of proportional weighting (Zheng et al. 2015; Dong et al., 2015). For symbols here and below see equations (3) and (4)

Step 1	$P_c = \frac{1}{1 + \frac{a_s D^b H^c}{a_c D^b H^c}} \times P_a$	$P_s = \frac{1}{1 + \frac{a_c D^b H^c}{a_s D^b H^c}} \times P_a$
Step 2a	$P_f = \frac{1}{1 + \frac{a_b D^b H^c}{a_f D^b H^c}} \times P_c$	$P_b = \frac{1}{1 + \frac{a_f D^b H^c}{a_b D^b H^c}} \times P_c$
Step 2b	$P_w = \frac{1}{1 + \frac{a_{bk} D^b H^c}{a_w D^b H^c}} \times P_s$	$P_{bk} = \frac{1}{1 + \frac{a_w D^b H^c}{a_{bk} D^b H^c}} \times P_s$

the logarithmic transformation of the variables (Baskerville 1972).

**RESULTS**

Initial regression equations are calculated:

$$\ln P_i = a_i + b_i(\ln D) + c_i(\ln H) + d_i(\ln D)(\ln H) + \sum g_{ij} X_j, \tag{3}$$

where  $P_i$  is biomass of  $i$ -th component, kg;  $i$  is the index of biomass component: aboveground ( $a$ ), crown ( $c$ ), stem over bark ( $s$ ), foliage ( $f$ ), branches ( $b$ ), stem wood ( $w$ ) and stem bark ( $bk$ );  $a_i \dots d_i$  are coefficients of numerous independent variables;  $j$  - index (code) of dummy variables, from 0 to 7 (Table 2).  $\sum g_{ij} X_j$  is the block of dummy variables for the  $i$ -th biomass component of the  $j$ -th ecoregion. After anti-log procedure model (1) has the form:

$$P_i = e^{a_i} D^{b_i} H^{c_i} D^{d_i(\ln H)} e^{\sum g_{ij} X_j} \tag{4}$$

According to the standard program of multivariate regression analysis, the coefficients of equations (3) are calculated and their characteristics are obtained, that after their corrections for the logarithmic transformation and its reduction to the form (4) is given in Table A.1 (Appendices). All regression coefficients of equations (4) for numerical variables are significant with a confidence of 0.95. The model is valid in the range of harvest data of tree height and stem diameter of sample trees given

in Table 2. The coefficient of determination for aboveground biomass is 0.991, and for biomass of stem, branches and foliage respectively are 0.992, 0.903 and 0.852 (Table A.1).

By substituting the regression coefficients of the initial equations from the Table A.1 (Appendices) in the structure of the AM presented in Table A.2 (Appendices), according to the two-step scheme of proportional weighing, the transcontinental AM of component composition of larch tree biomass with double harmonization was obtained, the final form of that is given in Table A.3 (Appendices). By tabulation of the resulting model (Table A.3) according to the given values of  $D$  and  $H$  and the value of the dummy variable  $X_6 = 1$ , a regional normative table was obtained, additive in biomass structure and intended for its use in the larch forests of Mongolia (Table 4).

Since the volume of all the tables for eight ecoregions exceeds the format of the journal article, we will limit ourselves to the comparison of some regional features of larch trees biomass structure by the corresponding fragment of the final Fig. 4 for the given diameter and height data.

**Table 4. Elaborated dry biomass table of the Siberian larch in Mongolia by tree height and stem diameter; unit values in kg**

Tree height, m	Biomass components	DBH, cm					
		10	14	18	22	26	30
10	Aboveground	24.14	42.97	66.07	-	-	-
	Tree crown	4.38	10.40	19.55	-	-	-
	Foliage	1.09	2.35	4.12	-	-	-
	Branches	3.29	8.05	15.43	-	-	-
	Stem and bark	19.77	32.57	46.52	-	-	-
	Stem wood	15.64	25.49	36.09	-	-	-
	Stem bark	4.12	7.08	10.43	-	-	-

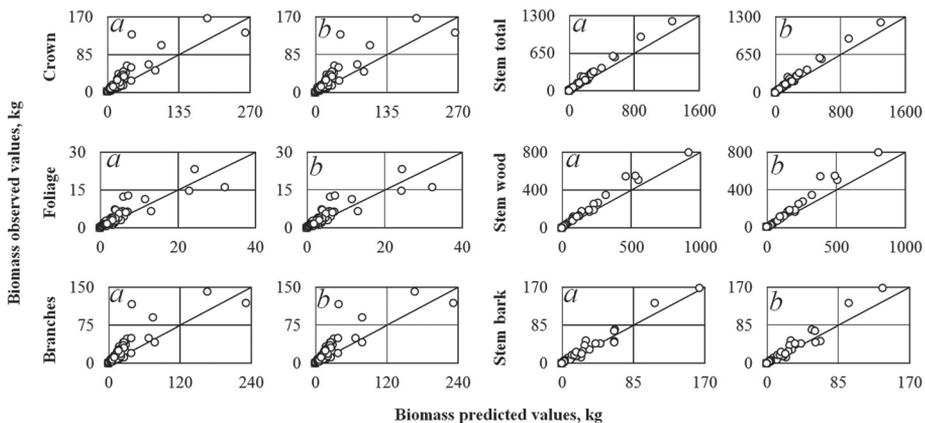
18	Aboveground	38.99	71.76	113.16	162.80	220.36	-
	Tree crown	2.16	5.67	11.60	20.43	32.59	-
	Foliage	0.55	1.31	2.49	4.12	6.22	-
	Branches	1.60	4.36	9.11	16.32	26.36	-
	Stem and bark	36.83	66.08	101.56	142.37	187.77	-
	Stem wood	30.83	54.72	83.39	116.08	152.18	-
	Stem bark	6.00	11.36	18.17	26.29	35.59	-
26	Aboveground	-	-	156.30	227.40	310.70	405.94
	Tree crown	-	-	7.53	13.66	22.39	34.12
	Foliage	-	-	1.63	2.78	4.30	6.24
	Branches	-	-	5.89	10.89	18.09	27.88
	Stem and bark	-	-	148.77	213.74	288.31	371.81
	Stem wood	-	-	125.80	179.51	240.73	308.86
	Stem bark	-	-	22.97	34.23	47.58	62.95

**Evaluation of the model**

Since it has been established that the elimination of the internal inconsistency of biomass equations by ensuring their additivity does not necessarily mean the increase in the accuracy of its estimates (Cunia and Briggs 1984; Reed and Green 1985), it is necessary to clarify whether the obtained AM is adequate enough and how its characteristics relate to the indices of the adequacy of initial equations.

The ratio of harvest biomass data and values obtained by the calculation of initial equations and AM of tree biomass, shows the degree of correlation of these values and the absence of visible differences in the structure of residual dispersions obtained from the two models (Fig. 4).

The results of the comparison indicate that there is no absolute superiority in terms of adequacy of either the initial or additive equations (Table 5).



**Fig. 4. The ratio of the harvest biomass and its values obtained by calculating the initial (a) and additive (b) models of the larch tree biomass**

**Table 5. Comparison of adequacy indices for the initial and additive equations of larch tree biomass**

Adequacy indices	Biomass components*						
	$P_a$	$P_s$	$P_w$	$P_{bk}$	$P_{cr}$	$P_b$	$P_f$
	Initial equations						
R <sup>2</sup>	0,973	0,989	0,974	0,956	0,613	0,585	0,624
RMSE	35,61	19,85	32,42	8,38	18,08	16,35	2,36
Bias	-1,91	-2,20	4,11	-1,79	-19,68	-20,90	-21,89
	AM						
R <sup>2</sup>	0,973	0,988	0,974	0,910	0,594	0,575	0,595
RMSE	35,61	20,63	32,48	11,92	18,53	16,55	2,45
Bias	-1,91	-2,09	-1,90	-8,89	-19,83	-20,91	-21,98

Note. \*Symbols designations see equation (3).

## DISCUSSION

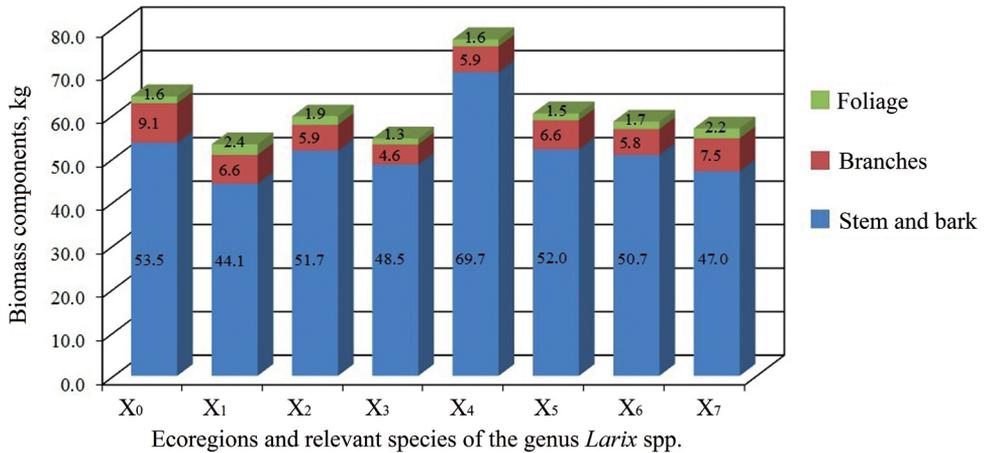
As shown in Table 4, patterns of changes in the structure of tree biomass in dependence of the value of stem diameter and tree height vary significantly. Biomass of all tree components significantly increases as the stem diameter increases, regardless of tree height. The stem biomass of trees having the diameter of 18 cm increases by 3.2 times, with an increase of tree height from 10 to 26 m. But foliage and branches biomass of the same stem diameter decreases with an increase of tree height by 2.5-2.6 times under influence of tree age. A negative relationship between the crown biomass of equal-sized trees and their age in forest stands is well known. For example, the crown mass of the tree with a diameter of 12 cm at the age of 15 years exceeds that at the age of 35 years at the birch by 1.5-2.0 times, and for the aspen – by 2.4-4.4 times (Usoltsev, 1972) due to the age shift of the cenotic position of equal-sized trees: at the age of 15 years such tree is the leader, and at the age of 35 years it is a depressed tree, a candidate for dying. Therefore, the share of participation of one or another biomass component and, accordingly, the cycling rate of larch substances will largely determine its distribution by the diameter

and height of trees.

### Comparison between biomass of larch trees from different Eurasian ecoregions. Ecological considerations

According to Fig. 5 the greatest values of tree aboveground biomass of equal both diameter and height occur in open larch communities growing on permafrost (77 kg), and in the rest of ecoregions the value of biomass is much lower (53-60 kg). Within this range there are trees in the mountains of Mongolia (58 kg). The intermediate position (64 kg) is occupied by the biomass of larch in Central Europe due to the abnormally developed crown of trees in 40-year-old plantations. The significant excess of larch biomass in the forest-tundra may be explained by permafrost conditions, by tree growth in low-yielding stands with a high basic density of stem wood (Hacke and Sperry 2001).

When following our results, the growing conditions of larch in Mongolia are approximately the same as in majority of other regions and not as tough as they are believed by Battulga et al. (2013). Our comparison of aboveground biomass by regions was made for trees with a stem diameter of 14 cm. Battulga et al. conclude



**Fig. 5.** Changes in the structure of the estimated biomass of trees with 14 cm diameter and 13 m height in different ecoregions. Designations: X<sub>0</sub> - Western and Central Europe, X<sub>1</sub> - European part of Russia, X<sub>2</sub> - Turgay steppe, X<sub>3</sub> - Western Siberia, the flood plain of the Pur river, X<sub>4</sub> - Eastern Siberia, forest-tundra, X<sub>5</sub> - Russian Far East, northern taiga, X<sub>6</sub> - mountains of Mongolia, X<sub>7</sub> - Japanese Islands

that there is more aboveground biomass in large trees of Mongolia compared with equal-sized trees of Iceland, and explain this phenomenon by more stringent growth conditions in the steppe compared to the conditions of Iceland. They compare the calculated indices of above-ground biomass. But if we compare the actual values of biomass of the trees having the diameter of 14 cm (see: Battulga et al., Fig. 2), then the differences are virtually absent. It is possible that the underestimation of biomass in Iceland due to the reduced basic density (climatic factor) is compensated by overestimation due to the more developed tree crown in plantations (cenotic factor) compared to the dense natural stands of Mongolia. Thus, some uncertainties in comparison biomass between ecoregions can be result of unaccounted and unknown regional features of age and morphological structures of forest stands.

The main part of the variability in the model (3) is assumed by the stem diameter and height, and the influence of unaccounted factors falls on the residual variance. The dummy variables confined to particular ecoregions extracted some portion of the variability from this residual variance. Belonging of the sample plots to these ecoregions mediates both climatic

and unaccounted ecological traits, and allometric biomass models including air temperature and precipitation, are known as models sensitive to climate variables (Zeng et al. 2017).

Nevertheless, we cannot know what proportion of the variability of the residual variance may be explained by involving climatic (regional) variables in the model, because this residual dispersion accumulates both unknown and unaccounted factors and errors of measurements in all their phases (assessment of age, diameter, height of a tree, the selection of supposedly representative samples of component biomass, their drying, weighing, etc.). The question of what explains the regional differences in the structure of biomass of trees with the same linear dimensions of their stems, remains open. Here, the differences in tree age play an undoubted role, as well as the variation in the morphological structure of stands, which, in turn, is determined by both climatic and edaphic factors. This will be the subject of further research.

The reasons for the relatively large bias values in both types of equations, especially for crown mass, can be seen in Fig. 5, showing the lack of homoscedasticity of

residual variance when the comparison is fulfilled on trivial (not log) coordinates: it extremely increases with increase of the crown biomass value. Accordingly, the biomass variability of the three to four largest trees contributes to the bias greater than the total residual bias of the remaining trees, and this phenomenon determines the large values of the biases. As a result, a slight overestimation or underestimation of the crown biomass of some single largest trees relative to the regression line determines the bias value, not peculiar to the biomass of the community of smallest trees.

The proposed AM, adapted for use in 8 ecoregions of Eurasia, is designed for a more accurate assessment of the carbon stock of larch forests. However, this is a solution to the problem only in the first approximation, because it is based on a limited amount of harvest data. If our database, containing 433 larch sample trees, may be supplemented with harvested (but not yet published) data on 600 larch trees in China (Zeng et al. 2017) and 96 trees in Poland (Jagodzinski et al. 2018), the model will get more consistent.

## CONCLUSIONS

1. On the basis of the obtained harvest biomass data of the Siberian larch trees in Mongolia and in comparison with similar data of other ecoregions of Eurasia,

a Trans-Eurasian AM of the genus *Larix* spp. biomass was developed, and thus the combined problem of additivity and regionality of the model was solved.

2. The AM of tree biomass of *Larix* is harmonized in two ways: it eliminated the internal contradictions of the component and of the aboveground biomass equations, and in addition, it takes into account regional (and correspondingly species) differences of equal-sized trees on its component structure.

3. The aboveground biomass of trees having the same sizes in the mountains of Mongolia is approximately the same as of the majority of the most ecoregions of Eurasia, with except for forest-tundra in the Far North.

4. The results obtained allow to determine larch forest biomass in different ecoregions of Eurasia when using the diameter and height tree measurement.

## ACKNOWLEDGEMENTS

This study was conducted in compliance with the programs of current scientific research of the Ural Forest Engineering University, Botanical Garden of the Ural Branch and V.N. Sukachev Institute of Forestry of Siberian Branch of Russian Academy of Sciences. ■

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Received on November 29<sup>th</sup>, 2018

Accepted on August 8<sup>th</sup>, 2019