PRINT ISSN 1119-8362
Electronic ISSN 1119-8362

Full-text Available Online at
https://www.ajol.info/index.php/jasem
http://ww.bioline.org.br/ja

J. Appl. Sci. Environ. Manage.
Vol. 24 (10) 1759-1766 October 2020

Additive Model of Aboveground Biomass of Larch Single-Trees Related To Age, Dbh and Height, Sensitive to Temperature and Precipitation in Eurasia

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ABSTRACT: The first attempt of modeling changes in the aboveground additive component composition of larch (genus *Larix* spp.) tree biomass, according to the Trans-Eurasian hydrothermal gradients of Eurasia on the database compiled for the structure of harvest biomass in a number of 510 sample trees is fulfilled. The adequacy of the obtained regularities is determined by the level of variability 87-99 % explained by the proposed regression models. For the central territory of European Russia, characterized by the mean annual temperature of January -10 °C and the mean annual precipitation of 400 mm, the increase in temperature by 1°C at the constant level of precipitation causes on *Larix* spp. trees of the equal age and sizes, the decrease in the aboveground, stem, needle and branches by 0.4, 0.3, 1.4 и 1.3 %, respectively. For the same region, in equal-sized trees, the increase in precipitation by 100 mm at a constant annual temperature in January causes the decrease of the aboveground and stem biomass by 1.2 and 1.7%, respectively, and the increase of needle and branches biomass by 4.0 and 6.0%, respectively. The development of such models for the main forest-forming species of Eurasia will make it possible to predict changes in the productivity of the forest cover of Eurasia in connection with climate change.

DOI: https://dx.doi.org/10.4314/jasem.v24i10.8

Dates: Received: 15 August 2020; Revised: 22 September 2020; Accepted: 19 October 2020

Keywords: larch trees, genus Larix spp., tree biomass, allometric models.

Forest biomass is an important part of sustainable development and the main driver of succession changes in secondary forests (Lohbeck *et al.* 2015), but the rate of recovery of their biomass is significantly faster than the rate of biodiversity recovery (Martin *et al.* 2013). This means a decrease in the stability of the biosphere and its gradual degradation, which poses a threat to human existence. Therefore, the removal of uncertainties related to the assessment of forest cover biological productivity and biodiversity is of paramount importance. Since the 19th century, researchers have noted that the relationships between the mass of individual parts and the whole organism in different species are well described by the so-called self-similarity function, or allometric one (Snell 1892, Dubois 1897, Huxley 1932, Gould 1966, Zar 1968, Ishchenko 1969, Mina and Клевезаль 1976, Kofman 1986, Gelashvili *et al.* 2013). Recently, a comparative analysis of the accuracy of different methods for determining the biological productivity of some tree species was fulfilled, and it was shown that allometric models designed at a tree scale give a smaller prediction error compared to models performed at the forest stand scale (Zeng *et al.* 2018). Such allometric models for mixed stands are particularly relevant. However, when calculating allometric models of tree biomass there is always a residual variance, reflecting, in particular, the discrepancy between the annual dynamics of the crown mass, especially of the foliage, and the relative conservatism of *D*, as an accumulator of its annual increments (Usoltsev 1988), as well as differences of age status, soil and climatic conditions. As shown by Kolmogorov (1933), the correlation measures only parallelism in the variability of variables, the source of which can be the action of the third variable, and in relation to such a complex object as a forest ecosystem, such "third" factors can be a great number. Having the aim of improving the accuracy of regional allometric models, one begins to involve in such models as predictors, along with *D*, such variables as average temperature and precipitation, which have, as it is well known, the geographical locality. Such models are called models sensitive to climate variables. However, they are presented as single, very seldom studies (Forrester *et al.* 2017, Zeng *et al.* 2017). All above mentioned models are internally contradictory, they are not harmonized by the biomass structure, i.e. they do not provide the additivity of component composition, according to which the total biomass of components

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(stems, branches, needles, roots) obtained by "component" equations would be equal to the value of biomass obtained by the total biomass equation (Dong *et al.* 2015). The need to respect the principle of additivity in the tables compiled for tree biomass on relevant equations, it was observed already in the first papers devoted to the evaluation of the biomass of trees (Young *et al.* 1964). In order to ensure the principle of additivity in the calculation of systems of equations for estimating the biomass of trees, several methods of their structuring are proposed. Models structured according to the principle "from particular to general" are divided into three groups: linear additive, nonlinear additive and nonlinear multiplicative (Kurucz 1969, Kozak 1970, Parresol 1999). An alternative variant, structured "from general to particular", has recently been suggested (Tang *et al.*, 2000). The structure of the disaggregated additive model is proposed, according to which the estimated aboveground biomass is divided into components (stem with bark, tree crown, branches, foliage) in accordance with their shares in the aboveground biomass. If estimates of intermediate biomass components are desirable, the estimated aboveground biomass is subdivided into intermediate components (e.g., stem and crown) according to their shares in the aboveground biomass. Further, the estimated biomass of the stem is divided into wood and bark according to their shares in the stem biomass, and the estimated biomass of the crown is divided into branches and foliage according to their shares in the crown biomass (Zheng *et al.* 2015). The influence of climate change on the biomass of trees of a particular tree species in the format of additive models according to trans-continental hydrothermal gradients has not been studied at all. In this study, the first attempt of modeling changes in the additive component composition of tree aboveground biomass according to hydrothermal Trans-Eurasian gradients is made. In the modeling process the database of biomass of 520 larch trees (genus *Larix* spp.) was used (Usoltsev 2016).

MATERIALS AND METHODS

Of the 520 sample trees described in the above-mentioned database containing data on biomass and dendrometric parameters, 420 trees were selected for the analysis, including six species-vicariants of the genus *Larix* spp. Their distribution by regions, tree species and mensuration indices is presented in Table 1. One hundred trees from the database were omitted in our analysis due to the lack of height measurements.

Table 1. Distribution of the 420 larch sample trees by ecoregions, tree species and mensuration indices

Regions	Species of the genus *Larix* spp.*	Ranges of:			Data number
		age, yrs	diameter *D*, cm	tree height, m	
West Europa	*L. decidua* Mill.	34÷210	7.1÷47.8	9.8÷34.0	19
European Russia	*L. sukaczewii* N.Dyl.	10÷70	1.0÷35.0	2.3÷28.0	25
Turgay deflection	*L. sukaczewii* N.Dyl.	26÷42	6.2÷28.0	7.9÷17.8	28
North of West Siberia	*L. sibirica* L. *L. gmelinii* Rupr.	10÷70	2.1÷38.0	2.9÷24.8	116
North of Eastern Siberia	*L. cajanderi* Mayr.	44÷400	0.3÷22.7	1.4÷14.8	66
North of Russian Far East	*L. cajanderi* Mayr. *L. gmelinii* Rupr.	30÷424	3.9÷52.8	2.9÷30.0	43
Mongolia, China	*L. sibirica* L. *L. gmelinii* Rupr.	14÷186	0.5÷31.0	1.5÷24.3	50
Japan	*L. leptolepis* Gord.	9÷56	4.0÷35.9	4.3÷26.7	73

* *Larix sukaczewii* N.Dyl. is a synonym of *L. sibirica* Ledebour; *L. cajanderi* Mayr. is a synonym of *L. gmelinii* (Rupr.) Kuzen.; and *L. sibirica* Ledebour = *L. decidua* Mill. ssp. *sibirica* (Ledeb.) Domin.

Table 2. The structure of the two-step additive model, sold under proportional weighting (Zheng *et al.* 2015, Dong *et al.* 2015). Symbols here and further as per equation (1)

Step 1	$P_c = \dfrac{1}{1+\dfrac{a_s D^{b_s} H^{c_s}}{a_c D^{b_c} H^{c_c}}} \times P_a$	$P_s = \dfrac{1}{1+\dfrac{a_c D^{b_c} H^{c_c}}{a_s D^{b_s} H^{c_s}}} \times P_a$
Step 2*a*	$P_f = \dfrac{1}{1+\dfrac{a_b D^{b_b} H^{c_b}}{a_f D^{b_f} H^{c_f}}} \times P_c$	$P_b = \dfrac{1}{1+\dfrac{a_f D^{b_f} H^{c_f}}{a_b D^{b_b} H^{c_b}}} \times P_c$
Step 2*б*	$P_w = \dfrac{1}{1+\dfrac{a_{bk} D^{b_{bk}} H^{c_{bk}}}{a_w D^{b_w} H^{c_w}}} \times P_s$	$P_{bk} = \dfrac{1}{1+\dfrac{a_w D^{b_w} H^{c_w}}{a_{bk} D^{b_{bk}} H^{c_{bk}}}} \times P_s$

where P_i is biomass of i-th component, kg; A is tree age, yrs; D is stem diameter at breast height, cm; H is tree biomass, m; i is the index of biomass component: aboveground (a), crown (c), foliage (f), branches (b), stem above bark (s), stem wood (w) and stem bark (bk); T is mean January temperature, °C; PR is mean annual precipitation, mm.

Based on the information in Table 2, the structure of the regression model is suggested as in eqn. 1:

$$\ln P_i = a_{0i} + a_{1i}(\ln A) + a_{2i}(\ln D) + a_{3i}(\ln H) + a_{4i}(\ln D)(\ln H) + a_{5i}[\ln(T+50)] + a_{6i}(\ln PR), \qquad (1)$$

Each sample plot on which tree biomass estimating was performed is positioned relatively to the isolines of the mean January temperature (Fig. 1) and relatively to the isolines of mean annual precipitation (Fig. 2). The matrix of harvest data was compiled, in which the biomass component values and mensuration tree parameters were related with the corresponding values of mean January temperature and precipitation, then included in the regression analysis procedure.

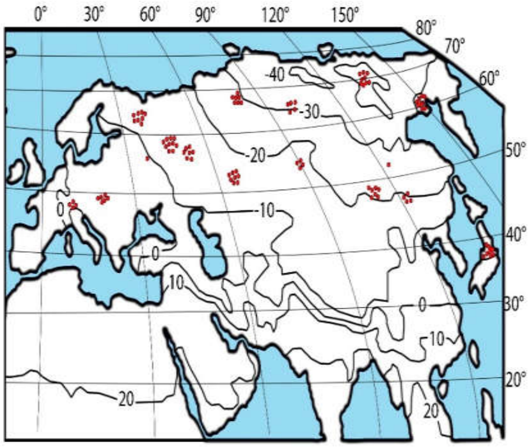

Fig 1. Distribution of biomass harvest data of 420 larch sample trees on the map of the mean January temperature, °C (World Weather Maps, 2007; https://store.mapsofworld.com/image/cache/data/map_2014/currents-and-temperature-jan-enlarge-900x700.jpg)

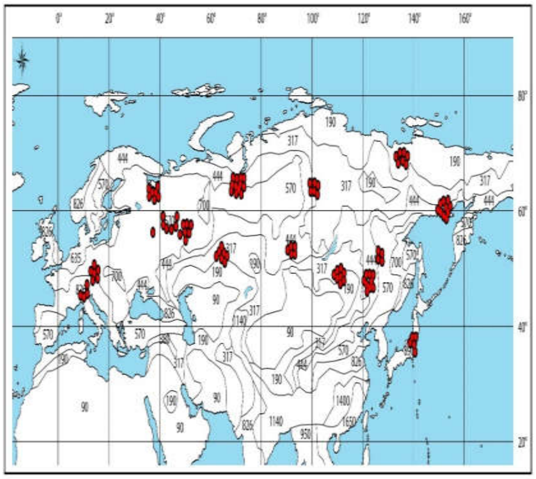

Fig 2. Distribution of biomass harvest data of 420 larch sample trees on the map of the mean annual precipitation, mm (World Weather Maps, 2007).

As noted above, the main predictor included in the allometric model of biomass is usually the stem diameter at breast height D. In this study, the task is to extract the climatic component from the residual dispersion of a model obtained during to calculation of tree biomass only by stem diameter. To made climatic factors to be predominant and "recoverable" from this "information noise", it is necessary to take into account in the model, in addition to the diameter, also tree height and age, which are factors that determine the structure of its biomass too (Nikitin 1965, Usoltsev 1972). According to the structure of the disaggregation two-step additive model (Zheng *et al.* 2015), the aboveground biomass P_a estimated by an initial equation is subdivided into components according to the scheme presented in Table 2. Since the mean January temperature in the northern part of Eurasia has negative values, the corresponding independent variable is modified to the form (T+50) to be subjected to log-log procedure. The schematic map of the isolines of mean January temperature, rather than the mean annual temperature, is used, since climate warming is most pronounced in the cold half of the year (Golubyatnikov and Denisenko 2009, Laing and Binyamin 2013, Felton *et al.* 2016). Along with the three main forest-forming variables - tree age, diameter and height –, the product of variables (ln$D$) (ln$H$) was introduced as an additional predictor, the need for which was shown earlier (Usoltsev *et al.*, 2017).

RESULTS AND DISCUSSION

Characteristic of equations (1) is obtained by the common regression analysis, and after correcting on logarithmic transformation by G. L. Baskerville (1972) and anti-log transforming is given in the Table 3. All regression coefficients of equations (1) are characterized by the significance level of 0.05 and better, and the resulting equations are adequate to the original values presented in the available database. The obtained initial equations (1) are transformed to the additive form according to the above mentioned algorithm (see Table 2) by two-step additive systems of disaggregation equations (Zheng *et al.* 2015). The final form of the transcontinental additive model of the component composition of the larch tree biomass is shown in Table 4. Since it was established (Cunia and Briggs 1984; Reed and Green 1985) that the elimination of the internal inconsistency of biomass equations by ensuring their additivity does not necessarily means the increase in the accuracy of its estimates, it is necessary to clarify whether the obtained additive model is adequate enough and how its characteristics relate to the indices of the adequacy of initial equations?

Table 3. Characteristics of initial equations (1)

Biomass component	Regression coefficients of the model							$adjR^2$*	SE*
P_a	0.486	$A^{-0.0529}$	$D^{1.5013}$	$H^{0.2183}$	$D^{0.1921(\ln H)}$	$(T+50)^{-0.1624}$	$P^{-0.0535}$	0.989	1.21
P_c	3.855	$A^{-0.5502}$	$D^{2.2014}$	$H^{-1.75642}$	$D^{0.3514(\ln H)}$	$(T+50)^{-0.5946}$	$P^{0.2090}$	0.908	1.63
P_s	0.165	$A^{0.0515}$	$D^{1.3387}$	$H^{0.7278}$	$D^{0.1527(\ln H)}$	$(T+50)^{-0.0897}$	$P^{-0.1145}$	0.990	1.21
P_f	2.995	$A^{-0.6569}$	$D^{2.1318}$	$H^{-1.6092}$	$D^{0.2932(\ln H)}$	$(T+50)^{-0.6478}$	$P^{0.1318}$	0.874	1.68
P_b	2.077	$A^{-0.5251}$	$D^{2.2978}$	$H^{-1.7649}$	$D^{0.3454(\ln H)}$	$(T+50)^{-0.5901}$	$P^{0.2201}$	0.907	1.67
P_w	0.232	$A^{0.0297}$	$D^{1.2737}$	$H^{0.8657}$	$D^{0.1713(\ln H)}$	$(T+50)^{-0.2036}$	$P^{-0.1890}$	0.992	1.20
P_{bk}	0.776	$A^{0.0306}$	$D^{1.2121}$	$H^{0.5622}$	$D^{0.1669(\ln H)}$	$(T+50)^{-0.2200}$	$P^{-0.4859}$	0.969	1.36

* $adjR^2$ – coefficient of determination adjusted for the number of parameters; SE – equation standard error.

Table 4. Final two-step additive model of tree biomass

Step 1	$P_a =$	$0.486\, A^{-0.0529} D^{1.5013} H^{0.2183} D^{0.1921(\ln H)} (T+50)^{-0.1624} P^{-0.0535}$	
	$P_c =$	$\dfrac{1}{0.165\, A^{0.0515} D^{1.3387} H^{0.7278} D^{0.1527(\ln H)} (T+50)^{-0.0897} P^{-0.1145}}$	$\times P_a$
	$P_s =$	$\dfrac{1}{3.855\, A^{-0.5502} D^{2.2014} H^{-1.75642} D^{0.3514(\ln H)} (T+50)^{-0.5946} P^{0.2090}}$	$\times P_a$
Step 2*a*	$P_f =$	$\dfrac{1}{2.077\, A^{-0.5251} D^{2.2978} H^{-1.7649} D^{0.3454(\ln H)} (T+50)^{-0.5901} P^{0.2201}}$	$\times P_c$
	$P_b =$	$\dfrac{1}{2.995\, A^{-0.6569} D^{2.1318} H^{-1.6092} D^{0.2932(\ln H)} (T+50)^{-0.6478} P^{0.1318}}$	$\times P_c$
Step 2*б*	$P_w =$	$\dfrac{1}{0.776\, A^{0.0306} D^{1.2121} H^{0.5622} D^{0.1669(\ln H)} (T+50)^{-0.2200} P^{-0.4859}}$	$\times P_s$
	$P_{bk} =$	$\dfrac{1}{0.232\, A^{0.0297} D^{1.2737} H^{0.8657} D^{0.1713(\ln H)} (T+50)^{-0.2036} P^{-0.1890}}$	$\times P_s$

$$A = \exp\{4.4904+0.6404(\ln D)-1.6043[\ln(T+50)]+0.5231(\ln PR)\};\ adjR^2=0.621;\ SE = 1.70 \quad (2);$$

$$H = \exp\{0.0648+0.0597(\ln A)+0.6372(\ln D)+0.2493[\ln(T+50)]-0.0467(\ln PR)\};adjR^2=0.895;\ SE = 1.21. \quad (3).$$

For this purpose both the additive model (see Table 4) and the initial equations (see Table 3), are tabulated on the actual data of age, stem diameter, height, and climatic variables, and the obtained calculated biomass values are compared with the actual ones according to R^2. The results of the comparison shown in the Figure 3, indicate that the additive system of equations have shown higher adequacy for all biomass components in comparison with initial ones. Due to the many times greater complexity of measuring the age and height of trees in comparison with *D*, one uses specially designed equations or tables (Usoltsev 1988). For this purpose, equations (2) and (3) is calculated to estimate the tree age *A* by the known value of the stem diameter *D,* as well as to estimate the tree height *H* by the known value of the tree age *A* and stem diameter *D*. Our analysis of the configuration of the surfaces obtained in three-dimensional space in Figure 4 allows to draw some nontrivial conclusions. Thus, in all thermal (zonal) belts (in the range of *T* from -40°C to 0°C) with increasing precipitation, the aboveground biomass and stem mass decreases, but the mass of tree needles and branches increases. Regardless of the level of precipitation during the transition from warm zones (*T* = 0°C) to cold ones (*T* = -40°C) all the biomass components increase. The obtained models of larch tree biomass make them possible to establish quantitative changes in the structure of tree biomass due to climatic changes, in particular, the mean temperature of January and mean annual precipitation. The percentage change in the structure of biomass is associated with the ratio of these two climatic variables. For the central territory of European Russia, characterized by the mean annual temperature of January -10 °C and the mean annual precipitation of 400 mm, the increase in temperature by 1 °C at the constant level of precipitation causes on larch trees at the age of 100 years with a diameter of 24 cm and stem height of 22 m, the decrease in the aboveground, stem, needle and branches by 0.4, 0.3, 1.4 and 1.3 %, respectively. For the same region, in equal-sized trees, the increase in precipitation by 100 mm at a constant annual temperature in January causes the decrease of the aboveground and stem biomass by 1.2 and 1.7%, respectively, and the increase of needles and branches biomass by 4.0 and 6.0%, respectively. In Figure 5 it is shown the change in the tree biomass (Δ, %) with an increase in temperature by 1°C in different ecoregions, characterized by different values of temperature and precipitation. It is assumed that climate change does not affect precipitation, which changes only geographically (by regions), and the temperature as a result of the expected climate change increases by 1°C at different territorial (zonal) temperature levels, designated as -40Δ...0Δ. Figure 5 shows the general pattern of decrease of all the biomass components of trees with an increase in temperature by 1°C in all temperature zones of Eurasia and in all regions that differ in precipitation. These trends are most pronounced in cold zones (T = -40°C) than in warm ones (T = 0°C).

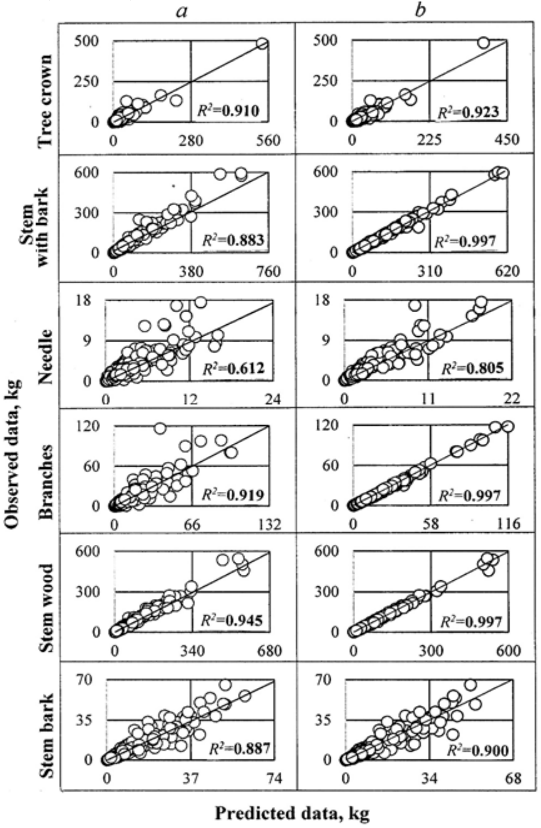

Fig 3. The ratio of the harvest biomass and its values obtained by calculating the initial (*a*) and additive (*b*) models of the larch tree biomass.

Since the tabulation of equations (1) using the given values A, D, H, T and PR results in a too cumbersome table, the required figures of the tree biomass dependence upon temperature T and precipitation PR are constructed as a fragment for trees having the age A equal 100 years, diameter D equal 24 cm and H equal 22 m (Figure 4). In Figure 6 it is shown the change of tree biomass (Δ, %) with the increase in precipitation by 100 mm in areas characterized by different values of temperature and precipitation. It is assumed that the January temperature changes only geographically, and precipitation as a result of the expected climate change increases by 100 mm at different territorial levels of precipitation, designated as 200Δ...900Δ.

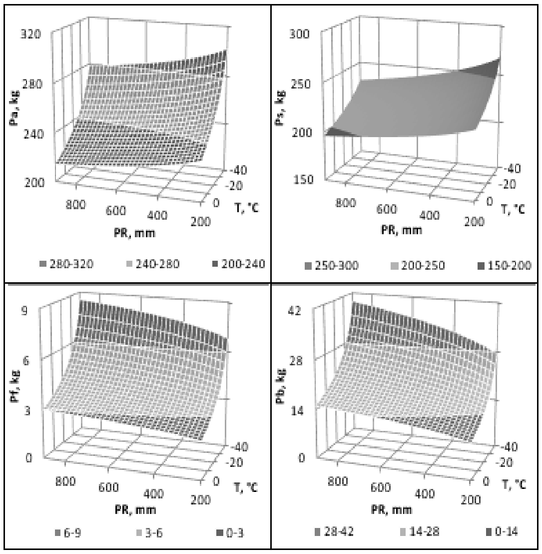

Fig 4. Dependence of larch tree biomass upon the January mean temperature (T) and precipitation (PR). Designations: *Pa, Ps, Pf,* and *Pb* are correspondingly biomass: aboveground, stems, foliage, and branches, kg

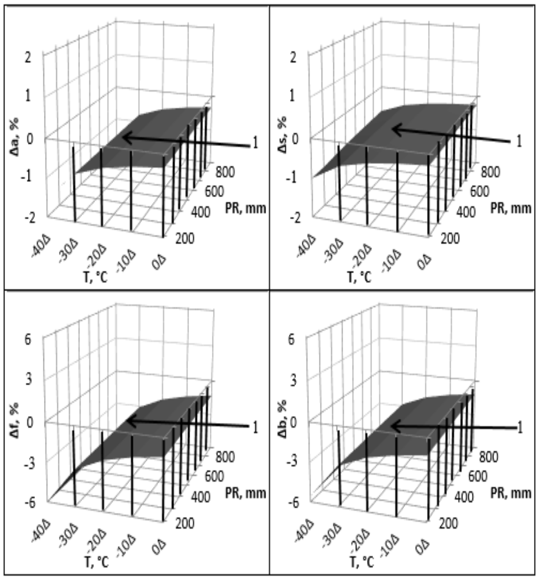

Fig 5. Change of tree biomass (surface 1) when temperature increasing by 1 °C due to the expected climate change at different territorial levels of temperature and precipitation. Symbols *Δa, Δs, Δf* and *Δb* on the ordinate axes mean the change (± %) of biomass of aboveground, stems, needles and branches, respectively, with the temperature increase by 1 °C and at the constant precipitation.

Figure 6 shows the common pattern of reducing the aboveground and stem biomass and of increasing the mass of needles and branches with an increase in annual precipitation by 100 mm in all temperature zones of Eurasia and in all regions that differ in precipitation. The trends mentioned are most strongly expressed in dry areas (*PR* =200 mm) than in enough wet ones (*PR* = 900 mm).

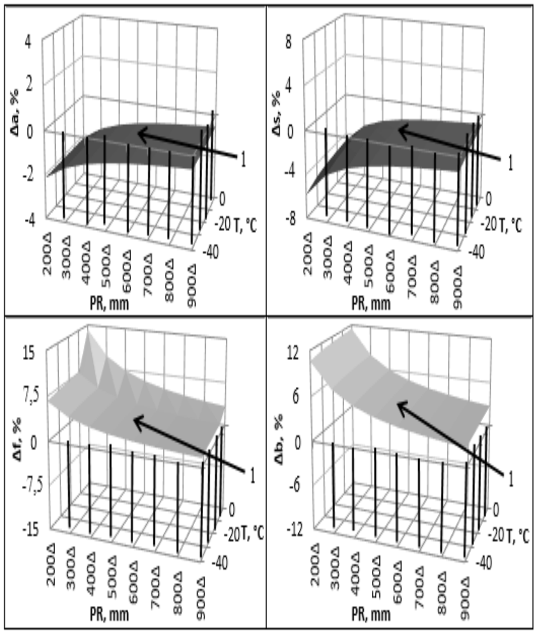

Fig 6. Change of tree biomass (surface 1) when precipitation increasing by 100 mm due to the expected climate change at different territorial levels of temperature and precipitation. The symbols *Δa, Δs, Δf* and *Δb* along the ordinate axes represent the change (± %) of aboveground, stems, needles and branches biomass, respectively, with precipitation increase by 100 mm and at the constant mean temperatures of January.

Our results only partially confirm the previously published data (Zeng *et al*. 2017) on the change in the aboveground biomass of larch trees with the increase in temperature by 1°C and with the increase in precipitation by 100 mm. In particular, the allometric model, which includes the diameter and stem height as independent variables, was developed for aboveground and underground biomass on the basis of 600 trees of eight larch species (genus *Larix* spp.) harvested throughout China. After introduction into the allometric model the indices of the mean annual temperature and precipitation, as additional independent variables, it is established that the temperature increase by 1°C leads to an increase in the aboveground biomass of equal-sized trees by 0.9%, and an increase in precipitation by 100 mm causes a decrease in the above- biomass by 1.5 % (Zeng *et al*. 2017). According to our results, there is a decrease in the aboveground biomass with an increase in both temperature and precipitation. We have found that in Russia the temperature raising by 1°C gives an decrease in the tree aboveground biomass by 0.4 %, and an increase in precipitation by 100 mm causes its decrease by 1.2 %. Thus, the aboveground biomass of larch in the boreal forests of Russia reacts negatively to the temperature increase, and in the temperate and subtropical forests of China reacts positively. With increasing precipitation, the aboveground biomass of trees in Russia and China is reduced, and in Russia compared with the forests of China it is to a lesser extent (1.2<1.5). In another study devoted to European forests (Forrester *et al*. 2017), there was no statistically significant effect of temperature and precipitation on the tree biomass of the most components. The reasons may be the following: a small range of temperature and precipitation variations within Europe, a study of species groups instead of a single species, the introduction of too many variables and their combined effects into the model, and the use of meta-data instead of harvest biomass indices. The study of the regional variability of the allometric models of aboveground biomass of trees of Masson pine in southern China showed that diameter at breast height, together with the long-term average of growing season temperature, total growing season precipitation, mean temperature of wettest quarter, and precipitation of wettest quarter, had significant effects on values of aboveground biomass. Excessive precipitation during the growing season and high mean temperature in the wettest quarter reduced the aboveground biomass, while a warm growing season and abundant precipitation in the wettest quarter increased it (Fu *et al*. 2017). Thus, the reaction of pine biomass to the increase in precipitation in the subtropical conditions of China in the wettest quarter is negative, and in the wettest quarter at extremely high temperatures is positive. A similar differentiated reaction of biomass and net primary production to temperature and precipitation was shown earlier on the example of stands of two-needled pines in Eurasia (Usoltsev *et al*. 2019).

Conclusions: Thus, we have made the first attempt to simulate changes in the component composition of the additive aboveground biomass of larch trees by Trans-Eurasian hydrothermal gradients. The obtained models of larch tree aboveground biomass make it possible to establish quantitative changes in the structure of larch biomass due to climatic changes, in particular, the mean January temperature and mean annual precipitation. They explain 87-99 % of the variability in tree biomass.

Acknowledgements: This paper was prepared within the programs of the current scientific research of the Ural Forest Engineering University and Botanical

Garden of the Ural Branch of Russian Academy of Sciences.

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