Acta Ecologica Sinica 41 (2021) 377–383

Contents lists available at ScienceDirect

Acta Ecologica Sinica

journal homepage: www.elsevier.com/locate/chnaes

Deterministic growth factors: Temperature and precipitation effect above ground biomass of Larix spp. in Eurasia

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ARTICLE INFO

Article history:
Received 26 November 2019
Received in revised form 19 March 2020
Accepted 2 June 2020
Available online 19 June 2020

Keywords:
Genus *Larix* spp.
Tree biomass
Pseudo-allometric models
Biological productivity
Mean January temperature
Mean annual precipitation

ABSTRACT

The aim of current study was to develop a generic pseudo-allometric model of the biomass structure of larch (*Larix* spp.) trees growing in Eurasia, and to assess the impacts of temperature and precipitation. It was assumed that this model will create a prerequisite for predicting changes in the structure of the tree biomass of the genus *Larix* spp. under the influence of current climate shifts. According to the Trans-Eurasian hydrothermal gradients of Eurasia harvest biomass database was compiled from 510 sample trees. The data adequacy was determined by the level of variability and it accounted for 87–99% variability as the proposed by regression models. It was found that the increase in temperature by 1 °C at the constant level of precipitation causes decrease in the aboveground, stem, foliage and branches of equal-sized and equal-aged larch trees. The increase of precipitation by 100 mm at the constant level of temperature causes decrease in the aboveground and stem biomass and increase of foliage and branches.

1. Introduction

International efforts are needed to prevent the rise in mean annual temperature and CO_2 emissions. Increased CO_2 emissions may be maintained while increasing vegetation biomass by means of effective forest management. Vegetation biomass and effective forest management help to reduce high mean annual temperature [1]. To estimate the biomass and carbon pools in the forested areas, allometric equations at a tree and stand levels are developed based on the harvest data obtained on the sample plots. It has been suggested that biomass of single forest type can be predicted while following traditional forest measurement indices [2].

Multivariate regression models have been implemented to assess biomass and net primary production of major forest structuring tree species of Eurasia [3–8]. Multivariate regression models are characterized by accuracy and reproducibility, however, these models fail to generalize on new samples or study areas [9,10]. It is relative important to evaluate the biomass of plant communities in different forest stands in other areas including mixed forests having different species composition. When using multivariate regression models to assess biomass and productivity in forest stand, there is possibility of biases, and the magnitude of these biases is unknown. A comparative analysis of the accuracy of different methods for determining biological productivity of some tree species showed that allometric models performed better at a tree level, and yielded smaller error in the assessment of biomass per area unit compared to models performed at a stand level [11].

It is known that the stem diameter at breast height (*DBH*) is a main predictor that explains the variation in tree biomass. *DBH* ~ tree biomass relation is the most common, as illustrated by the allometric function. Allometry demonstrates how functions are correlated with tree architecture. Allometric relationships are important component of vegetation models and help to scale processes from individuals to globe level. Optimization theory may pave the way for development of allometric relationship; however allometry does not explain empirical observation [12,13]. Biomass models work best when tree heights are included in models along with DBH, while incorporating Cobb-Douglas model [14–20]. Its log-log transformation is following

$$lnPi = a + b\, ln(DBH) + c\, lnH \qquad (1)$$

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https://doi.org/10.1016/j.chnaes.2020.06.002
1872-2032/

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

Regions	Species of the genus *Larix* spp.[a]	Ranges			Data number
		Ages, yrs	Diameters, cm	Heights, 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

[a] *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.

Where, Pi is dry biomass of *i*-th component, kg; DBH and H are respectively the stem diameter at the breast height (cm) and the tree height (m).

Trees of the same diameter and height, have different ages, therefore variation occurs in biomass, especially in crown biomass [21]. Hence, it is necessary to include tree age along with DBH and height in the model, as tree age determines the structure of tree biomass [22–28]. After including tree age in allometric model, tree biomass takes following form.

$$lnPi = a + b\ lnA + c\ ln(DBH) + d\ lnH \quad (2)$$

In Eq. (2), the tree age is an ontogenetic factor, and H is the tree height. *DBH* at the same age mediates the coenotic factor, and the tree height at the same age and *DBH* is an indirect edaphic factor. Along with the three main mass-forming variables - tree age (*A*), diameter at breast height (*DBH*) and height (*H*) of a tree, the product of variables (ln*DBH*), (ln*H*) was introduced into Eq. (2) as an additional predictor, due to the fact that as a tree height decreases, the height of the measurement of a *DBH* shifts to the stem apex, and the allometry is violated [29]. So, we propose to call this modified allometry as pseudo-allometry having the form.

$$lnPi = a + b\ lnA + c\ ln(DBH) + d\ lnH + e\ (lnDBH)(lnH) \quad (3)$$

Since the Eq. (3) includes the main mass-forming independent variables, it can be considered as a generic one. But this assumption is acceptable for the total aboveground biomass only [30–32], but not for biomass component equations [33].

If we calculate Eq. (3) as a generic, using all available harvest data for Eurasia, and then applying it at different local levels, we will have biases of estimates. These biases are most likely due to natural zoning mediated by temperature and precipitation [34,35]. By introducing temperature and precipitation indices as additional independent variables into Eq. (3), we obtained the model sensitive to climate variables. Such sensitive model has been reported previously [36]. The aim of current study was to develop a generic pseudo-allometric model of the structure of the biomass of larch (*Larix* spp.), single-trees species growing in Eurasia. Second aim was to assess the impacts of temperature and precipitation on the structure of biomass. According to our knowledge there is no literature available on the biomass structure of a single tree of a given tree species in the Trans-Eurasian along the temperature and precipitation gradients. We hypothesized that temperature and precipitation will affect tree biomass. Particularly, we were interested to check the impacts

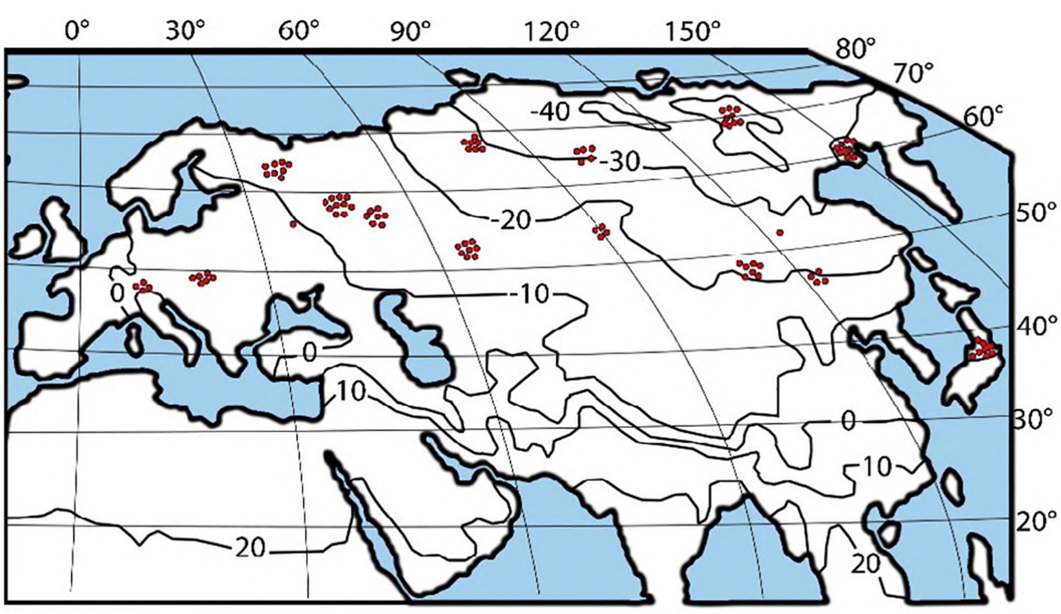

Fig. 1. Distribution of biomass harvest data of 420 larch sample trees on the map of the mean. January temperature, °C (World Weather Maps, 2007; https://store.mapsofworld.com/image/cache/data/map_2014/currents-and-temperature-jan- enlarge-900 × 700.jpg).

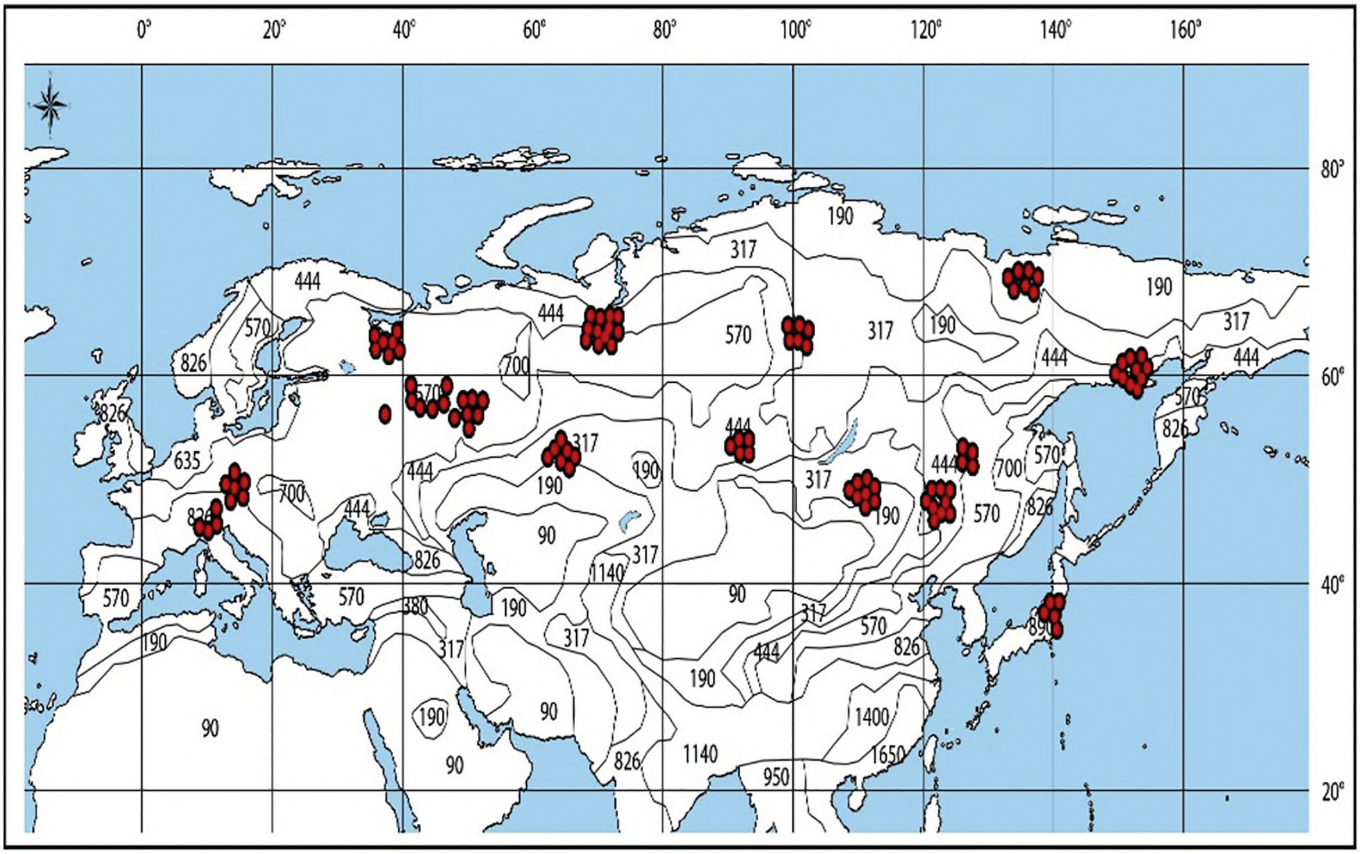

Fig. 2. Distribution of biomass harvest data of 420 larch sample trees on the map of the mean annual precipitation, mm (World Weather Maps, 2007).

of temperature by 1 °C at the constant level of precipitation. Does temperature decrease biomass of equal aged larch tree?

2. Materials and methods

Among 520 sample trees biomass database including dendrometric parameter, 420 trees were selected for the analysis. We excluded 100 trees due to the lack of height measurements data. The biomass data distribution by regions and measurement indices are presented (Table 1). Tree biomass estimation was carried out in sampling plots. Sampling plots position was relative to the isoclines (contour lines) of the mean January temperature (Fig. 1), and mean annual precipitation (Fig. 2). Harvest data matrix was generated including this climatic indices, as well as biomass component values and mensuration tree parameters. These component values and mensuration tree parameters were included in the regression analysis procedure. As indicated Fig. 1, mean January temperature in the northern part of Eurasia has negative values, therefore the corresponding independent variable was modified to the form $(T + 50)$, which was subjected to logarithmic procedure. As climate warming is more pronounced in arctic region during the half of the year [37,38], therefore schematic map of the isoclines of mean January temperature, rather than the mean annual temperature was used. This corresponds to the well-known fact that the temperature in the arctic rises more rapidly than in the rest of the earth territory [39]. We used following structure of the regression model:

$$lnP_i = a_{0i} + a_{1i}\,(lnA) + a_{2i}\,(lnDBH) + a_{3i}\,(lnH) + a_{4i}\,(lnDBH)(lnH) + a_{5i}[ln(T+50)] + a_{6i}(lnPR) \quad (4)$$

where P_i is biomass of i^{th} component, kg; i is the index of biomass component: stem over bark (P_s), foliage (P_f), branches (P_b) and aboveground (P_a); T is mean January temperature, °C; PR is mean annual precipitation, mm. All the necessary calculations were carried out in statgraphics software (http://www.statsgraphics.com).

Given the complexity of measuring the age and height of trees in comparison with DBH, it is recommended to use specially designed equations [4]. Therefore, Eqs. (5) and (6) are calculated to estimate the value of A by the known values of the DBH, and to estimate the value of H by the known values of A and DBH.

Table 2
Characteristics of Eq. (1).

Biomass component	Regression coefficients of the model							$adjR^2$ [a]	SE [a]
P_a	0.486	$A^{-0.0529}$	$D^{1.5013}$	$H^{0.2183}$	$D^{0.1921(\ln H)}$	$(T+50)^{-0.1624}$	$PR^{-0.0535}$	0.989	1.21
P_s	0.165	$A^{0.0515}$	$D^{1.3387}$	$H^{0.7278}$	$D^{0.1527(\ln H)}$	$(T+50)^{-0.0897}$	$PR^{-0.1145}$	0.990	1.21
P_f	2.995	$A^{-0.6569}$	$D^{2.1318}$	$H^{-1.6092}$	$D^{0.2932(\ln H)}$	$(T+50)^{-0.6478}$	$PR^{0.1318}$	0.874	1.68
P_b	2.077	$A^{-0.5251}$	$D^{2.2978}$	$H^{-1.7649}$	$D^{0.3454(\ln H)}$	$(T+50)^{-0.5901}$	$PR^{0.2201}$	0.907	1.67

[a] The abbreviation $adjR^2$ is a coefficient of determination adjusted for the number of parameters; SE – equation standard error.

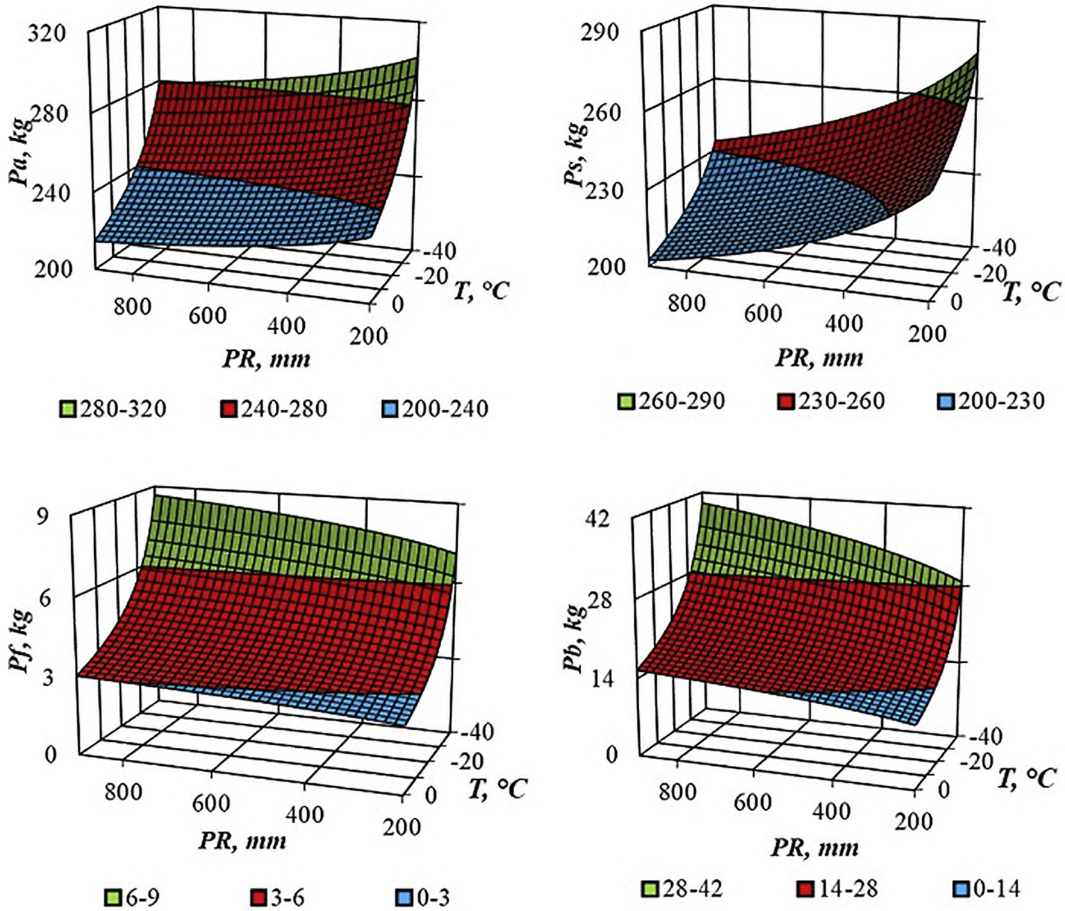

Fig. 3. Dependence of larch tree biomass upon the January mean temperature (T) and precipitation (PR). Designations: Pa, Ps, Pf, and Pb are correspondingly biomass: aboveground, stems, foliage, and branches, in kg.

$$A = exp.\{4.4904 + 0.6404(lnD) - 1.6043[ln(T + 50)] + 0.5431(lnPR)\};$$
$$adjR^2 = 0.621; SE = 1.70 \tag{5}$$

$$H = exp.\{0.0648 + 0.0597(lnA) + 0.6372(lnD) + 0.2493[ln(T + 50)]$$
$$-0.0467(lnPR)\}; adjR^2 = 0.895; SE = 1.21 \tag{6}$$

3. Results

Eq. (4) was obtained by the trivial regression analysis, while following logarithmic transformation as suggested by [40]. Log and anti-log transforming are presented (Table 2). Regression coefficients of Eqs. (4), (6) are characterized by the significance level of 0.05 and the resulting equations are adequate to predict or explain available database.

Since the tabulation of Eq. (4) using the given values *A, DBH, H, T* and *PR* results in lengthy table, therefore figures of the tree biomass dependence upon temperature *T* and precipitation *PR* were constructed as a fragment of 3D-graphs for trees. We showed tree biomass dependence on temperature (T) and precipitation (PR). Trees age (100 years) were plotted along with diameter D (24 cm) and stem (22 m) (Fig. 3). 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 foliage 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 (Fig. 3).

Increase in temperature by 1°C in different eco regions altered tree biomass (Δ, %), and eco regions had different values of temperature and precipitation (Fig. 4). We observed 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 (Fig. 4). Tree biomass (Δ, %) changed with increasing precipitation and temperature. Different values of temperature and precipitation were recorded (Fig. 5). The common pattern of reduced above ground and stem biomass were reported, whereas needle biomass and branches had positive correlation with annual precipitation (Fig. 5). These trends mentioned are most strongly expressed in dry areas (PR =200 mm) than in enough wet ones (PR = 900 mm).

4. Discussions

We showed that biomass is associated with the ratio of these two climatic variables i.e. temperature and precipitations. Current study revealed temperature and precipitation are important factors for allocation of biomass in different parts of trees. Our results partially confirm the previously published data [36], 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.

According to our results, there is a decrease in the aboveground biomass with an increase in both temperature and precipitation. It is rational to find such results, as we have found that in Russia the temperature rising by 1°C decrease in the tree aboveground biomass by 0.4%, and an

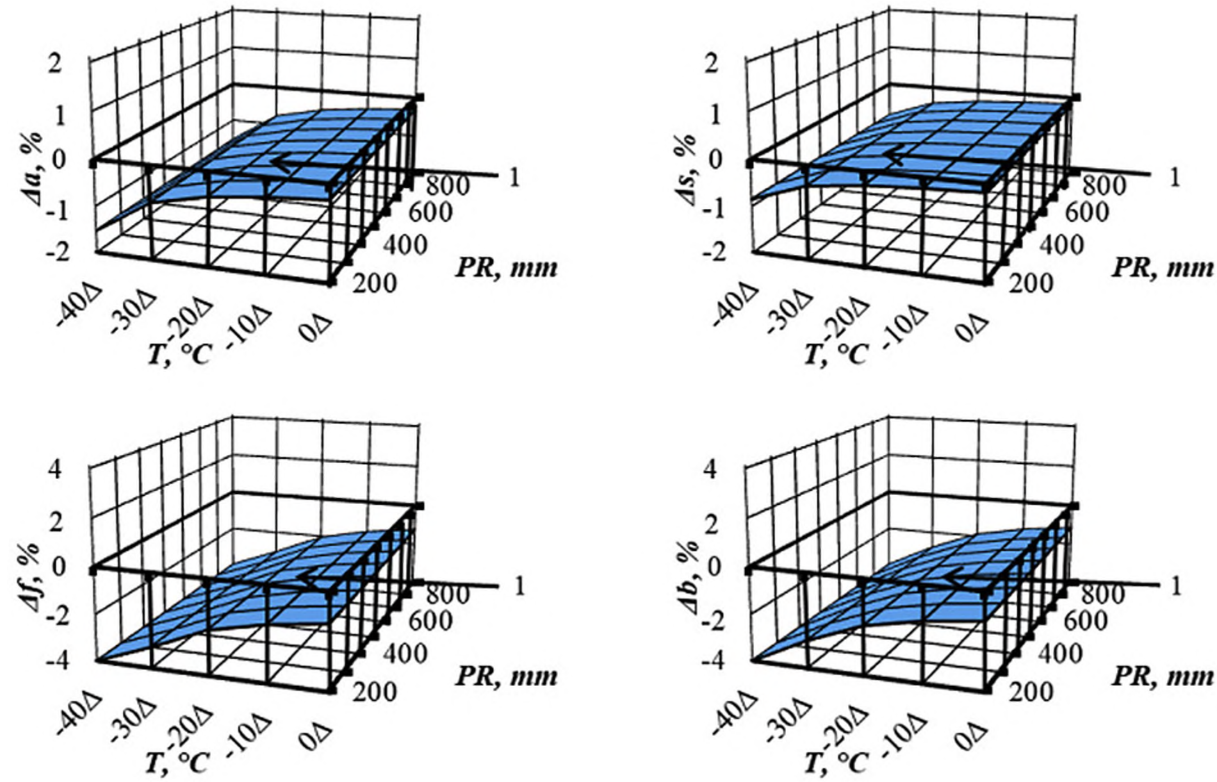

Fig. 4. Change of tree biomass (surface 1) when winter temperature increasing by 1°C due to the expected climate change at different territorial levels of temperature and precipitation. Symbols Δa, Δs, Δf and Δb on the ordinate axes mean the change (± %) of biomass of aboveground, stems, foliage and branches, respectively, with the temperature increase by 1°C and at the constant precipitation.

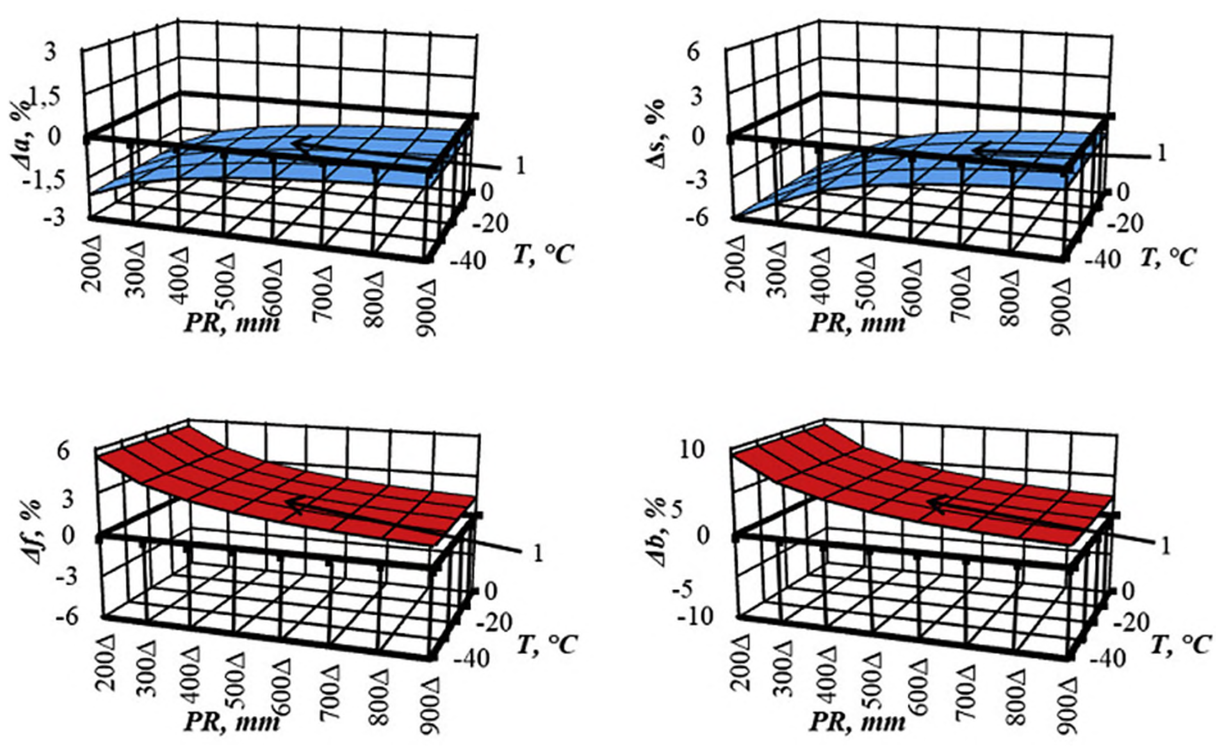

Fig. 5. Change of tree biomass (surface 1) when precipitation increasing by 100 mm due to the expected climate change at different territorial levels of temperature and precipitation. The symbols Δa, Δs, Δf and Δb along the ordinate axes represent the change (± %) of aboveground, stems, needles and branches biomass, respectively, with precipitation increase by 100 mm and at the constant mean temperatures of January and at the constant precipitation.

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.

Several studies have found variable results. For example, it was revealed that no statistically significant effect of temperature and precipitation on the tree biomass of the most components, owing to a small range of temperature and precipitation variations groups' species including many variables and use of meta-data instead of harvest biomass indices [41]. Scientific literature shows that temperature is the main determining factor which explains allocation of tree biomass and has revealed positive and negative impact on plant growth, for instance, [42], showed that root total biomass increased, where as in contrast to root total biomass, foliage biomass decreased.

Allometric model studies of aboveground biomass of trees of Masson pine in southern China showed that high mean temperature reduced aboveground biomass, whereas precipitation had antagonistic effect [43]. A similar differentiated response of biomass and net primary production to temperature and precipitation was shown earlier on the example of stands of two-needled pines in Eurasia [44].

5. Conclusions

The intensity of biomass trend in relation to the temperature of precipitation was studied. We showed that the increase in winter temperature by 1°C at the constant level of precipitation causes decrease in the aboveground, stem, foliage and branches of equal-sized and equal-aged larch trees. The increase of precipitation by 100 mm at the constant level of winter temperature causes decrease in the aboveground and stem biomass and increase of foliage and branches. 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 relation to climate change.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This paper was prepared within the programs of the current scientific research of the Ural Forest Engineering University, Botanical Garden of the Ural Branch of Russian Academy of Sciences..

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