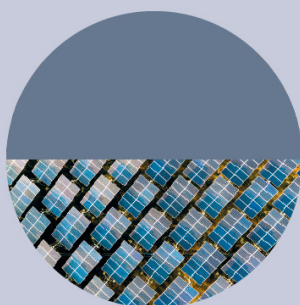**PAPER • OPEN ACCESS**

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What is a possible response of forest biomass to changes in Eurasian air temperature and precipitation? A special case for the genus *Betula* spp.

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Abstract. Forest ecosystems, as sinks of atmospheric carbon, play an important role in reducing greenhouse gas release and preventing air temperatures from rising. Simultaneously, climate change entails changes in forest cover. We describe the change of *Betula* spp. stand biomass (t ha^{-1}) along the trans-Eurasian gradients of rainfall and temperature using the harvest data from 650 forest stands and climate data. Birch stand biomass increased with growing rainfall within the evaluated range from 200 to 800 mm per year, as well as with increasing the mean winter temperature from -40°C to +10°C regardless of the rainfall level. The comparison of our results for birches with analogous results for coniferous species shows that forest responses to changes in climate indices are species-specific.

1. Introduction

Climate change requires reliable assessment of carbon pools in plant ecosystems [1]. The estimation of phytomass reserves with high accuracy is of a great importance for the characterization of forest ecosystem function. Information on phytomass not only contributes to a better describing energy processes in tree ecosystems, but is also an indicator of their ecological sustainability [2]. At the UN climate summit in Paris in 2015, 196 countries committed themselves to reducing greenhouse gas release and preventing climate warming by more than 2°C by the end of current century. Forest ecosystems, as sinks of atmospheric carbon, play the main role in this perspective. On the other hand, climate change entails in the structure and functions of the biota changes, including forest cover that is accounting for biomass about 80% of total over-ground organic carbon stocks and 40% of underground carbon stocks [3]. Therefore, any removal of uncertainties with the estimation of forest cover phytomass and biodiversity in relation to climate warming is of paramount importance.

Warm and rainfall are the most informative climatic variables influencing forest stand biological productivity [4-8]. A lot of studies of regression relationships of stand phytomass with warm indices and rainfall have been fulfilled at a regional level without taking into account stand morphology, and at a global level even without taking in mind tree species involving in stand structure [9-11].

Not only in scientific, but also in a civilizational aspect, it is interesting what will happen to our biota with the temperature changing, for example, by 1°C and when rainfall changes, for example, by 100 mm per year. Some published the single-tree biomass models that called as the models sensitive to climate peculiarities, give an answer to a similar question on forest trees. However, they are presented as single,

very seldom studies. It was developed for phytomass of 600 trees of eight larch species (genus *Larix* spp.) harvested throughout China. After accounting for air temperature and rainfall into the allometric model, supplementary to stem sizes, it was revealed that the warming by 1°C leads to an increase in the aboveground tree phytomass by 0.9% and to a decrease in the root one by 2.3%, An increase in rainfall by 100 mm causes a decrease in the aboveground phytomass and root one by 1.5 and 1.1%, respectively [2]. In another study devoted to European forests [12], there was no statistically significant effect of temperature and precipitation on the tree biomass of the most fractions. 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. Today, the tree phytomass production change of single species under influence of the climate along the Trans-Eurasia' change of temperature and rainfall is studied very seldom [13-15], and the needed information is not enough [6, 16-18]. Birch (*Betula* spp.) is a genus comprising more 120 species belonging to the *Betulaceae* CA Agardh. family, 40 of which are presented in Russia. There are several species in the common birch category from the section *Albae* Rgl. [19]. This question has been investigated on coniferous species only [13-15].

The aim of our work was to design a model of phytomass change in birch (*Betula* spp.) stands as a reaction to climate warming and rainfall change along to the Trans-Eurasian area. The database suggested by V A Usoltsev [16, 17] makes it possible to analyze phytomass (eventually for carbon) at the continental level.

2. Methods and Materials

The database on biomass of forest-forming species of Eurasia [16, 17] consisting of data published by a large number of authors was used in the modeling process of this work. From this database, 650 sampling sites with the phytomass data of birch forest stands were selected. In most cases, from 5 to 10 model trees were taken on each of sample plots. Then samples were taken from each phytomass fraction to obtain the dry matter content and the basic density of wood and after drying them, the results were extended to a tree level. The pool of phytomass fractions per 1 ha was calculated by regression software. But some sampling technologies differed between the publications, since they were performed by different scientists of forestry. Not all phytomass fractions are equally involved in the database: if the phytomass of stems over bark, branches and foliage is estimated on the all 650 plots, the phytomass of the stem bark on 275, of roots on 310 and of understorey (the sum of grasses, brushes and ingrowth) on 320 plots. Data on birch phytomass are represented in Eurasia as follows: Central and Western Europe - 93, Russia - 360, Kazakhstan -58, China -130 and Japan - 9 definitions (table 1).

Table 1. List of 650 biomass data (t/ha) in *Betula* spp. used for biomass models.

Species of *Betula*	Country	Number of sampling sites
Betula pendula Roth. *B. pubescens* Ehrh.	Russia, Ukraine, Kazakhstan, Great Britain, Belarus, Azerbaijan, Finland, Japan, Sweden, Mongolia, Lithuania, Belgium, Norway, France, Denmark (Greenland)	500
B. utilis D.Don	China	127
B. tortuosa Ldb.	Russia	9
B. platyphylla Suk.	China, Russia, Japan	6
B. ermanii Cham.	China, Japan	4
B. maximowicziana Rgl.	Japan	4
Total		650

The matrix of phytomass data representing individual components and forest stand characteristics was combined with the mean January temperature (figure 1) and rainfall (figure 2) data taken from World Weather Maps [18].
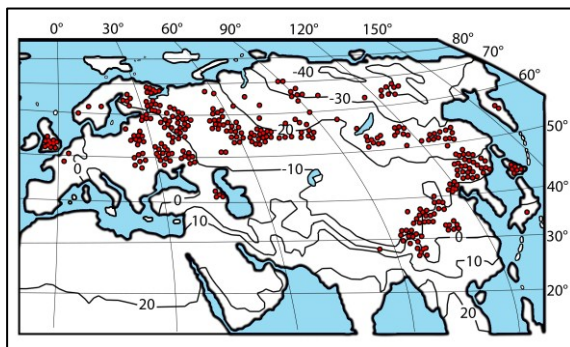
Figure 1. Distribution of 650 sample plots, where *Betula* trees have been harvested, on the map of the mean winter temperature, C [18].
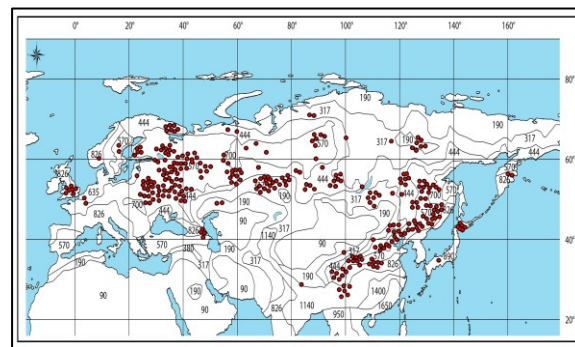
Figure 2. Distribution of 650 sample plots, where *Betula* trees have been harvested, on the map of the mean annual rainfall, mm [18].

The efficiency of forest object analyzing depends on the level of correctness of an initial analysis of harvest data. This principle means to be taken into account the most active range of data values [19]. There is some analogy with the similar process at a continental level: air warming at the Earth's poles and altitudinal limits increases much more compared to that of the rest land [20-23]. Therefore, we use the winter temperature as the most correct to describe the climate warming. The effectiveness of a regression model depends upon the ratio of total and residual variance too. The relationship is more reliable, the more the total variance against the same residual one. Obviously, taking the mean winter temperature instead of mean annual one, we get a more reliable dependence having the higher predictive ability. Besides, to ensure the effectiveness of our result, each of the involved variables should be in the maximum diapason of its variability [24]. In our study, mean January temperatures ranges from -40°C to +10°C, and mean annual rainfall differs from 190 mm to 1,140 mm in the area of Eurasia.

When choosing the form of an empirical model, we take in mind the rule that there is only single option of stand phytomass structure related to a given set of taxonometric indices of a forest [25]. Therefore we involve into our model the main mass-determining variables – age, stem volume and tree number per ha, not mutually correlated. The final structure of the model includes only those mass-forming indices that were statistically significant for all biomass fractions. The general regression equation is:

$$\ln P_i = a_{0i} + a_{1i}(\ln A) + a_{2i}(\ln V) + a_{3i}(\ln N) + a_{4i}(\ln A) \cdot (\ln N) + a_{5i}\left[\ln(Tm + 50)\right] + a_{6i}(\ln PRm). \qquad (1)$$

In (1) P_i is phytomass of ith fraction, t/ha; A is tree age, yrs; V is stem volume, m^3/ ha; N is tree density, 1000 individuals per ha; i is index of phytomass fraction as follows: total wood storey (*t*), understorey (*u*), aboveground (*a*), underground (*r*), stem over bark (*s*), foliage (*f*), and crown skeleton (*b*); PRm is mean annual rainfall, mm; Tm is mean January temperature, °C. Since the winter temperature at the North of Eurasia is minus (figure 2), this independent variable is modified as (Tm+50). To tabulate equation (1) we calculate the auxiliary models [26]:

$$N = f\left[A, (Tm + 50), PRm\right], \qquad (2)$$

$$V = f\left[A, N, (Tm + 50), PRm\right]. \qquad (3)$$

3. Results and Discussion
The models are designed using the correction by Baskerville [27] and they are characterized by the significance level of at least 0.05 (table 2, 3). From the results of their tabulating we took the calculated data of phytomass fractions for the age of 50 years and designed 3D-picture of their relation to temperature and rainfall (figure 3). As we can see from figure 3, the phytomass of the most of fractions in 50-year-old birch stands increased as annual rainfall and winter temperature are growing.

Table 2. Characteristics of biomass equations (1).

Biomass components	Regression coefficients of the model							$adjR^{2a}$	SE^b
Pt	5.8057	$A^{-0.0345}$	$V^{0.7813}$	$N^{-0.3137}$	$A^{0.0795\,\ln N}$	$(Tm+50)^{-0.0481}$	$PRm^{-0.0798}$	0.943	1.18
Pu	0.0052	$A^{0.3668}$	$V^{-0.0474}$	$N^{-0.2501}$	$A^{0.0694\,\ln N}$	$(Tm+50)^{0.6425}$	$PRm^{0.5034}$	0.121	2.33
Pa	1.2499	$A^{-0.0106}$	$V^{0.9028}$	$N^{-0.0162}$	$A^{-0.0008\,\ln N}$	$(Tm+50)^{0.0099}$	$PRm^{-0.0276}$	0.975	1.14
Pr	4.9132	$A^{0.0929}$	$V^{0.5196}$	$N^{-0.4772}$	$A^{0.1279\,\ln N}$	$(Tm+50)^{-0.0780}$	$PRm^{-0.1387}$	0.633	1.50
Ps	0.8408	$A^{-0.0553}$	$V^{0.9929}$	$N^{-0.0804}$	$A^{0.0196\,\ln N}$	$(Tm+50)^{-0.0630}$	$PRm^{0.0016}$	0.980	1.14
Pf	0.1388	$A^{0.0251}$	$V^{0.5438}$	$N^{0.2360}$	$A^{-0.0355\,\ln N}$	$(Tm+50)^{0.3562}$	$PRm^{-0.1479}$	0.486	1.57
Pb	0.6307	$A^{0.1424}$	$V^{0.6278}$	$N^{0.0190}$	$A^{-0.0366\,\ln N}$	$(Tm+50)^{0.3591}$	$PRm^{-0.3073}$	0.780	1.45

[a] $adjR^2$ – determination coefficient adjusted for the number of variables;

[b] SE – standard error of the equation in the original dimension Pi (t/ha).

Table 3. Characteristics of the auxiliary equations.

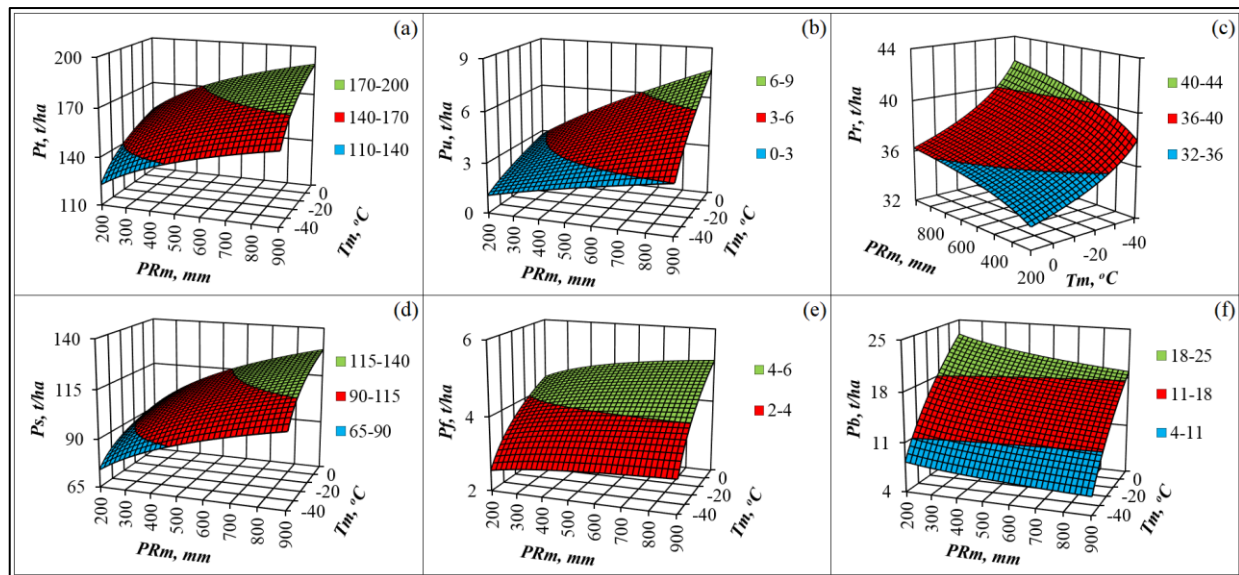| Mass-forming indices	The auxiliary equations characteristics					$adjR^2$	SE
$\ln N$	5226.3	$A^{-1.6448}$	-	-	$(Tm+50)^{-1.1071}$ $PRm^{0.3929}$	0.631	2.25
$\ln V$	1.1227	$A^{0.8703}$	$N^{-0.3795}$	$A^{0.1259\,\ln N}$	$(Tm+50)^{0.4301}$ $PRm^{0.0281}$	0.615	1.68

Figure 3. The dependence of birch stand biomass upon mean January temperature (Tm) and annual rainfall (PRm) at the standage of 50 years. Designation: Pt, Ps, Pu, Pf, Pr, and Pb – biomass: total (above- and underground), stems over bark, understory, foliage, roots (underground), and branches, t per ha, respectively.

It is well known the Liebig's law of the minimum [28], according to which the growth rate depends on the factor that is at the minimum in relation to its needs. Although J. Liebig, followed by J Esslen [29], had shown that a limiting factor can be not only a lack, but also an excess of such factors as light, heat and moisture (a lot of "good" - also "not good"), nevertheless, he focused his attention on the effect of the minimum of chemicals (oxygen, phosphorus, boron, etc.), and as a result of that the phenomenon was established in science as the law (principle) of the minimum by Liebig.

The idea of the limiting influence of the maximum on a par with the minimum was developed by V Shelford [30], who extended the limiting principle to any environmental factors and became known as the author of Shelford's law of tolerance. W P Taylor [31] followed the same concept. Later A A Molchanov [32] interpreted the limiting principle in relation to forest ecosystems as an "extended concept of limiting factors", according to which "any state approaching or exceeding the limit of resistance for any organism and groups of interest can be considered as a limiting factor". Recently, this phenomenon has become widespread as the principle of limiting factors by Liebig-Shelford [33].

The results obtained by us confirmed the extended concept of limiting factors on the example of climatic gradients of biomass of the genus *Betula* spp. within Eurasia, i.e. we quantified the reaction of the biomass structure of stands to the deficit or excess of heat in conditions of sufficient moisture supply and to the deficit or excess of moisture in conditions of sufficient air temperature.

The reaction of biomass structure of birches both on increase in temperature, and on increase in rainfall is similar to the corresponding reactions of firs [13]: with an air temperature increase, the largest increases in biomass occur in cold areas (-30°C...-40°C) and approach zero in warm ones (+10°C). With increasing precipitation, the greatest increase in biomass occurs in dry areas and approaches zero in wet ones.

Reaction of spruces [14] to changes in climate variables is similar to the response of birches only in part: if, with increasing temperature, the greatest increases in biomass occur in cold areas (-30°C...-40°C) and approach zero in warm areas (+10°C), then their response to increased precipitation differs. In particular, spruces have an increase in biomass in warm areas (+10°C) and the decrease in cold ones (-30°C), and in both cases this phenomenon does not depend on the level of rainfall in regions.

The greatest differences of birches, associated with their phytomass reaction to climatic variables, are observed with two-needled pines, both at the levels of trees [15] and stands [34]: in the conditions of warm shortage with sufficient moisture supply (Northern Siberia' regions), the air temperature increase leads to the increase in the productivity of trees and stands of pines, but the increase in rainfall leads to its decrease. In conditions of moisture deficiency with sufficient warm supply (steppe part of Central Asia), the temperature increase causes the decrease in productivity, and the increase in rainfall, on the contrary, its increase.

This demonstrates the confirmation of the limiting factor principle already mentioned: in conditions of a lack of moisture or heat, any increase in precipitation or temperature exacerbates the limitation, and biomass decreases, and vice versa. It is also clear that forest responses to changes in climate variables are species-specific.In order to understand possible impacts of climate change on biological productivity of forest cover and to obtain sufficiently adequate simulation results of this relationship, it is necessary to provide experimental data on productivity and climate variables in the widest possible range of their variation, i.e. at global or continental levels. In a recent work [35], geographical coordinates of sample plots, as well as annual rainfall and temperature were included in the model of forest productivity for the territories of Germany and the United States along with main defining independent variables, and the results were somewhat uncertain. We assume that the evidence of the authors is contradictory because: (1) climate variables are correlated with geographical coordinates of sample plots in this model, and (2) the ranges of variability of climate variables within a country were too small to obtain stable patterns. To avoid such uncertain results, the transcontinental level of analysis was chosen in our study, and geographical coordinates were not included among independent variables.

The results presented may be considered as preliminary ones. They can be modified if the biomass database will be supplemented by new data, mainly site-specific and stand-specific characteristics as well as by more advanced and correct methodologies.

4. Conclusion
The model presented is designed using the phytomass data of 650 birch stands and climatic variables. It is revealed that the most of phytomass fractions of birch forests is changed as following: phytomass grows with the increasing rainfall in the diapason from 200 to 800 mm per year, as well as with increase in the January temperature from -40°C to +10°C regardless of the rainfall level.

Acknowledgements

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