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Modeling the additive structure of stand biomass equations in climatic gradients of Eurasia

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Abstract

It has been established that in cold climatic zones any increase in rainfall leads to a corresponding decrease in biomass volume and in warm zones an increase in rainfall leads to an increase in biomass value. Furthermore, in water-rich areas (900 millimeters [mm] per year), a rise in temperature causes an increase of biomass values, whereas in arid areas (300 mm per year) it causes reductions. These statements confirm previously recognized results that other researchers documented at both local and regional levels. For natural and planted tree stands, these patterns follow suit, but in absolute terms plantation biomass shows annual increases in total biomass, roots, stems, needles, and branches, of 16, 18, 11, 2, and 3%, respectively, compared to natural stands. The percentage of change in the structure of biomass is related to the ratio of the two climatic indices—temperature and rainfall. In particular, for the central part of European Russia, the Russian Far East, and northeastern China, which are characterized by mean annual temperatures in January of –10 degrees Celsius (°C) and mean annual precipitation of 500 mm, any temperature increase of 1°C at a constant level of precipitation increases biomass of stands aged 100 years in total biomass, roots, stems, needles, and branches, by 2.2, 1.8, 2.5, 0.36, and 2.3%, respectively, regardless of the origin of the stands. In the same regions and with pine stands of the same age, a precipitation increase of 100 mm at an unchanged mean temperature reduces total biomass, roots, stems, and needles by 5.8, 2.3, 6.5, and 0.3%, respectively, and increases branch biomass by 0.3%. The development of such models for the basic forest-forming species grown in Eurasia will make it possible to predict changes in the biological productivity of the forest cover of Eurasia related to climate change.

KEYWORDS
additive biomass equations, annual mean precipitation, annual mean temperature, biological productivity, biosphere role of forests, forest biomass, allometric model, two-needled pines

1 | INTRODUCTION

In recent years, there has been an explosion in the development of methods for evaluating forest biological productivity in relation to what has been observed due to climate change from the 1960s through the 1980s (Budyko, 1977; Laing & Binyamin, 2013), as predicted at the end of the 19th century in the works of "the father of global warming," Svante Arrhenius (1896). Because climate change affects natural zones in a localized manner, which was established as a result of a long evolution of vegetation (Kosanic, Anderson, Harrison, Turkington, & Bennie, 2018; Mäkipää, Villén-Peréz, Salemaa, & Heikkinen, 2015), climatic change inevitably entails changes in vegetation productivity (Fang, Wang, & Shao, 2016; Schaphoff, Reyer, Schepaschenko, Gerten, & Shvidenko, 2016). To predict the impacts of climate change on forest productivity, one must know the linkages between forest biomass and climate indices (Stegen et al., 2011).

The most informative climate factors that determine forest productivity are temperature and precipitation. For the whole of the American continents from Canada in the North to the South of Chile (from 55°N to 41°S), it has been revealed that the biomasses of dry tropical and temperate forest stands of varied species and morphological structures depend on mean annual precipitation ($R^2 = 0.37–0.39$). The index of annual precipitation to mean annual temperature in humid tropical forests is positive ($R^2 = 0.13$), and in the forests with an excess of hydration it is negative, although not statistically significant ($R^2 = 0.02$; Stegen et al., 2011).

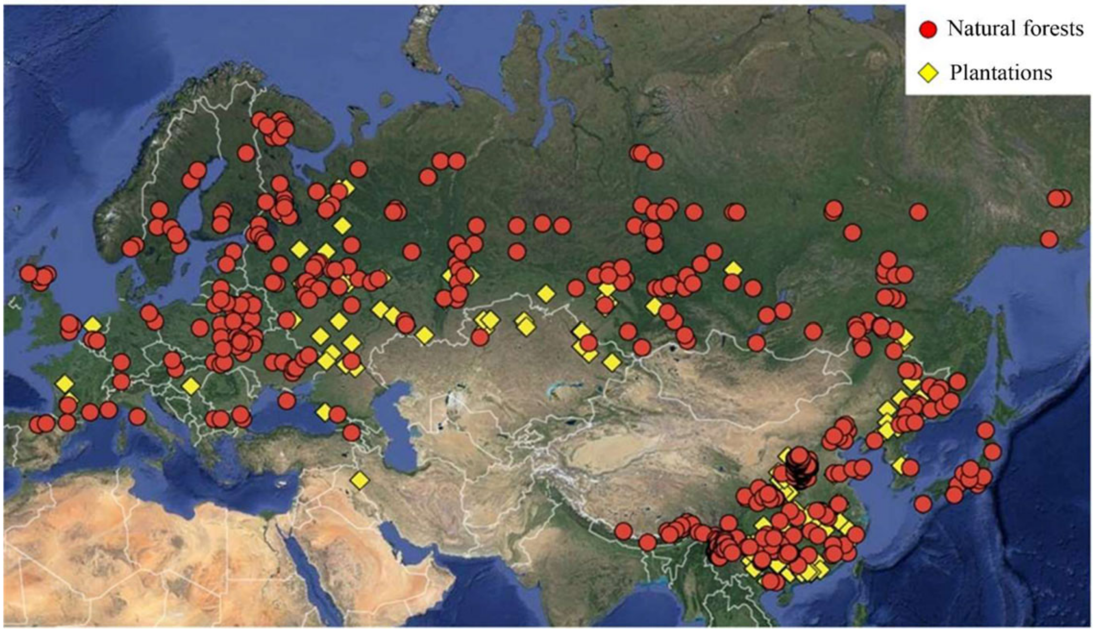

EXHIBIT 1 Allocation of sample plots with biomass (t/ha) determinations in a number of 2,460 pine (subgenus *Pinus*) forest stands in the territory of Eurasia [Color figure can be viewed at wileyonlinelibrary.com]

Using 1,340 sample plots established in six forest biomes for basic forest-forming species in China, Ni, Zhang, and Scurlock (2001) showed direct positive dependences of net primary production (NPP) based on mean annual precipitation ($R^2 = 0.42–0.86$) and, in a somewhat less pronounced fashion, on mean annual temperature ($R^2 = 0.31–0.60$).

Analysis by Fang et al. (2016) of the variability of Korean cedar NPP in the Changbai Mountains in China, which correlated with radial growth over the past 50 years, showed that two-factor linear dependence of the mentioned indices on the minimum temperature in April and summer precipitation explains 28% of the total variability of NPP, while this relationship with both indices was positive (Fang et al., 2016).

A study of sensitivity to climate variables of allometric models of aboveground and underground *Larix* sp. single-tree biomass in a territory in China showed that an increase in mean annual temperature by 1 degree Celsius (°C) leads to an increase in aboveground biomass of equal-sized trees of 0.87%, but a decrease in underground biomass of 2.26%. However, an increase in average annual precipitation at 100 millimeter (mm) reduces aboveground and underground biomass by 1.52 and 1.09%, respectively (Zeng et al., 2017).

Thus, numerous studies of stochastic dependencies of forest productivity on temperature and precipitation have been carried out on a regional level—although in most cases without providing indices of stand age and morphology—and on global level, without taking into account species composition. This has led to problems in determining the impact of climate change on the productivity of single species (genera) in transcontinental gradients, as the available information is sketchy and contradictory. Thus, actual impacts are unknown.

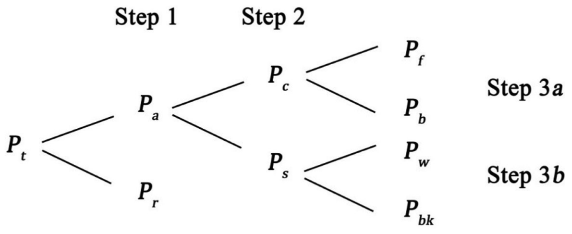

EXHIBIT 2 The pattern of disaggregating three-step proportional weighting additive model Designations P_t, P_r, P_a, P_c, P_s, P_f, P_b, P_w, and P_{bk} are stand biomass, respectively: total, underground (roots), aboveground, crown (needles and branches), stems above bark (wood and bark), needles, branches, stem wood, and stem bark correspondingly in tons per hectares (t/ha)

In this study, we first attempt to model changes using additive component composition of forest-stand biomass of two-needled pines according to the annual mean temperature and precipitation of Eurasian gradients, taking into account regional particularities of age and stand morphology indices. Additivity of component composition means that the total biomass of its components (e.g., stems, branches, foliage, roots), derived from component equations, must be equal to the result obtained using the common equation (Bi et al., 2010). The database of stand biomass for forest-forming species in Eurasia is used in the process of modeling (Usoltsev, 2013).

2 | MATERIALS AND METHODS

The database used in this study defines 2,460 sample plots with forest stand biomass in tons per hectares (t/ha) (**Exhibit 1**). These

EXHIBIT 3 Characteristics of initial equations for pine forests

Biomass components	Equations and their regression coefficients											$adjR^{2a}$
P_t	41.8764	$A^{-0.0947}$	$A^{0.0191(\ln A)}$	$M^{0.8283}$	$N^{0.0072}$	$X^{-0.0347}$	$(Tm+40)^{-1.7081}$	$(Tm+40)^{0.0431\ln(Tm+40)}$	$PRm^{-0.1754}$	$PRm^{-0.0555\ln(PRm)}$	$(Tm+40)^{0.2542\ln(PRm)}$	0.947
Step 1												
P_a	22.8823	$A^{-0.2524}$	$A^{0.0397(\ln A)}$	$M^{0.8241}$	$N^{0.0035}$	$X^{0.0499}$	$(Tm+40)^{-1.7443}$	$(Tm+40)^{0.0781\ln(Tm+40)}$	$PRm^{0.0069}$	$PRm^{-0.0547\ln(PRm)}$	$(Tm+40)^{0.2180\ln(PRm)}$	0.951
P_r	2.05E-05	$A^{0.9526}$	$A^{-0.0931(\ln A)}$	$M^{0.6941}$	$N^{0.0777}$	$X^{0.0331}$	$(Tm+40)^{2.9224}$	$(Tm+40)^{-0.0952\ln(Tm+40)}$	$PRm^{0.8842}$	$PRm^{0.0237\ln(PRm)}$	$(Tm+40)^{-0.3447\ln(PRm)}$	0.799
Step 2												
P_c	1.10E+06	$A^{-0.6671}$	$A^{0.0599(\ln A)}$	$M^{0.5288}$	$N^{-0.0328}$	$X^{0.0008}$	$(Tm+40)^{-3.2616}$	$(Tm+40)^{-0.0174\ln(Tm+40)}$	$PRm^{-2.3831}$	$PRm^{0.0572\ln(PRm)}$	$(Tm+40)^{0.5547\ln(PRm)}$	0.621
P_s	0.2990	$A^{0.3529}$	$A^{-0.0276(\ln A)}$	$M^{0.9205}$	$N^{0.0257}$	$X^{0.0625}$	$(Tm+40)^{-1.4144}$	$(Tm+40)^{0.1821\ln(Tm+40)}$	$PRm^{0.5701}$	$PRm^{-0.0585\ln(PRm)}$	$(Tm+40)^{0.0584\ln(PRm)}$	0.965
Step 3a												
P_f	2.00E+05	$A^{-0.5871}$	$A^{0.0318(\ln A)}$	$M^{0.4393}$	$N^{0.0347}$	$X^{0.0306}$	$(Tm+40)^{-1.2510}$	$(Tm+40)^{-0.0071\ln(Tm+40)}$	$PRm^{-3.0048}$	$PRm^{0.2042\ln(PRm)}$	$(Tm+40)^{0.1945\ln(PRm)}$	0.430
P_b	9.48E+04	$A^{-0.4754}$	$A^{0.0424(\ln A)}$	$M^{0.5825}$	$N^{-0.0836}$	$X^{-0.0026}$	$(Tm+40)^{-4.8746}$	$(Tm+40)^{0.0094\ln(Tm+40)}$	$PRm^{-1.1818}$	$PRm^{-0.1021\ln(PRm)}$	$(Tm+40)^{0.7994\ln(PRm)}$	0.652
Step 3b												
P_w	0.0393	$A^{0.5888}$	$A^{-0.0563(\ln A)}$	$M^{0.9291}$	$N^{0.0009}$	$X^{0.1303}$	$(Tm+40)^{-1.1127}$	$(Tm+40)^{0.0328\ln(Tm+40)}$	$PRm^{0.8231}$	$PRm^{-0.0952\ln(PRm)}$	$(Tm+40)^{0.1504\ln(PRm)}$	0.967
P_{bk}	1.97E+19	$A^{0.4697}$	$A^{-0.0291(\ln A)}$	$M^{0.6603}$	$N^{0.1812}$	$X^{0.0792}$	$(Tm+40)^{-8.0281}$	$(Tm+40)^{0.7813\ln(Tm+40)}$	$PRm^{-11.3663}$	$PRm^{0.8013\ln(PRm)}$	$(Tm+40)^{0.4980\ln(PRm)}$	0.785

[a] $adjR^2$ – coefficient of determination adjusted for the number of parameters.

Notes: P_i = biomass of *i*-th component in tons per hectare (t/ha); *i* = index of biomass component: total (t), aboveground (a), roots (r), crowns (c), stems above bark (s), needles (f), branches (b), stem wood (w), and stem bark (bk); *A* = stand age in years (years); *M* = stem volume in cubic meters per hectare (m^3/ha); *N* = tree density, 1000 per hectare (1000/ha); *X* = dummy variable: for natural pines $X = 0$ and for pine plantations $X = 1$; PR*m* = mean annual precipitation, in millimeters (mm); *Tm* = January mean annual temperature in degrees Celsius (°C). Because the January mean annual temperature in Northern Eurasia has negative values, the corresponding independent variable is modified to the form ($Tm + 40$).

EXHIBIT 4 The final form of the additive biomass model

$Pt = 41.8764A^{-0.0947}A^{0.0191(\ln A)}M^{0.8283}N^{0.0072}X^{-0.0347}(Tm+40)^{-1.7081}(Tm+40)^{0.0431(\ln Tm+40)}PRm^{-0.1754}PRm^{-0.0555(\ln PRm)}(Tm+40)^{0.2542(\ln PRm)}$	
Step 1	$Pa = \frac{1}{1+8.95\mathrm{E}{-07}A^{1.2051}A^{-0.1328(\ln A)}M^{-0.1300}N^{0.0742}X^{-0.0168}(Tm+40)^{4.6666}(Tm+40)^{-0.1733(\ln Tm+40)}PRm^{0.8773}PRm^{0.0784(\ln PRm)}(Tm+40)^{-0.5627(\ln PRm)}} \times Pt$
	$Pr = \frac{1}{1+1.12\mathrm{E}{+06}A^{-1.2051}A^{0.1328(\ln A)}M^{0.1300}N^{-0.0742}X^{0.0168}(Tm+40)^{-4.6666}(Tm+40)^{0.1733(\ln Tm+40)}PRm^{-0.8773}PRm^{-0.0784(\ln PRm)}(Tm+40)^{0.5627(\ln PRm)}} \times Pt$
Step 2	$Pc = \frac{1}{1+2.72\mathrm{E}{-07}A^{1.0200}A^{-0.0875(\ln A)}M^{0.3916}N^{0.0585}X^{0.0617}(Tm+40)^{1.8472}(Tm+40)^{0.1995(\ln Tm+40)}PRm^{2.9531}PRm^{-0.1157(\ln PRm)}(Tm+40)^{-0.4964(\ln PRm)}} \times Pa$
	$Ps = \frac{1}{1+3.68\mathrm{E}{+06}A^{-1.0200}A^{0.0875(\ln A)}M^{-0.3916}N^{-0.0585}X^{-0.0617}(Tm+40)^{-1.8472}(Tm+40)^{-0.1995(\ln Tm+40)}PRm^{-2.9531}PRm^{0.1157(\ln PRm)}(Tm+40)^{0.4964(\ln PRm)}} \times Pa$
Step 3a	$Pf = \frac{1}{1+0.4740A^{0.1117}A^{0.0106(\ln A)}M^{0.1432}N^{-0.1183}X^{-0.0332}(Tm+40)^{-3.6237}(Tm+40)^{0.0165(\ln Tm+40)}PRm^{1.8230}PRm^{-0.3063(\ln PRm)}(Tm+40)^{0.6049(\ln PRm)}} \times Pc$
	$Pb = \frac{1}{1+2.1097A^{-0.1117}A^{-0.0106(\ln A)}M^{-0.1432}N^{0.1183}X^{0.0332}(Tm+40)^{3.6237}(Tm+40)^{-0.0165(\ln Tm+40)}PRm^{-1.8230}PRm^{0.3063(\ln PRm)}(Tm+40)^{-0.6049(\ln PRm)}} \times Pc$
Step 3b	$Pw = \frac{1}{1+5.02\mathrm{E}{+20}A^{-0.1191}A^{0.0272(\ln A)}M^{-0.2688}N^{0.1802}X^{-0.0512}(Tm+40)^{-6.9154}(Tm+40)^{0.7484(\ln Tm+40)}PRm^{-12.1894}PRm^{0.8965(\ln PRm)}(Tm+40)^{0.3476(\ln PRm)}} \times Ps$
	$Pbk = \frac{1}{1+1.99\mathrm{E}{-21}A^{0.1191}A^{-0.0272(\ln A)}M^{0.2688}N^{-0.1802}X^{0.0512}(Tm+40)^{6.9154}(Tm+40)^{-0.7484(\ln Tm+40)}PRm^{12.1894}PRm^{-0.8965(\ln PRm)}(Tm+40)^{-0.3476(\ln PRm)}} \times Ps$

Notes: P_i = biomass of *i*-th component in tons per hectare (t/ha); *i* = index of biomass component: total (t), aboveground (a), roots (r), crowns (c), stems above bark (s), needles (f), branches (b), stem wood (w), and stem bark (bk); *A* = stand age in years (years); *M* = stem volume in cubic meters per hectare (m^3/ha); *N* = tree density, 1000 per hectare (1000/ha); *X* = dummy variable: for natural pines $X = 0$ and for pine plantations $X = 1$; *PRm* = mean annual precipitation, in millimeters (mm); *Tm* = January mean annual temperature in degrees Celsius (°C). Because the January mean annual temperature in Northern Eurasia has negative values, the corresponding independent variable is modified to the form $(Tm + 40)$.

plots include 1,480 plots of natural forest and 980 of planted forests. Subgenus *Pinus* sp. is present in 86% of the plots, including Scots pine (*Pinus sylvestris* L.) and in smaller quantities by the following species: *P. tabuliformis* Carr., *P. densiflora* S. et Z., *P. nigra* Arn., *P. pinaster* Aiton, *P. pithyusa* (STEVEN) SILBA, and *P. thunbergii* Parl. Each sample plot, in which the biomass of the forest stands was estimated, is positioned in accordance to January mean annual temperature isolines and to mean annual precipitation isolines, and the initial data matrix is compiled in which the values of biomass components and of stand taxonomy characteristics are mated with corresponding values of mean annual temperature and precipitation. The matrix is then subjected to regression analysis.

According to the structure of the disaggregated three-step model (Dong, Zhang, & Li, 2015), its total biomass, estimated by the original equation, is exploded into component equations according to the scheme presented in **Exhibit 2**. The coefficients of the regression models for all three steps are evaluated simultaneously, which ensures the additivity of the biomass components: the total, intermediate, and initial ones (Dong et al., 2015).

3 | RESULTS AND DISCUSSION

The original regression equations are designed as follows:

$$\begin{aligned}\ln P_i = {} & a_{0i} + a_{1i}(\ln A) + a_{2i}(\ln A)^2 + a_{3i}(\ln) + a_{4i}(\ln N) + a_{5i} \\ & + a_{6i}\left[\ln(Tm+40)\right] + a_{7i}\left[\ln(Tm+40)\right]^2 + +a_{8i}(\ln PRm) \\ & + a_{9i}(\ln PRm)^2 + a_{10i}[\ln(Tm+40)]\cdot(\ln PRm) \qquad (1)\end{aligned}$$

where P_i, biomass of *i*th component (t/ha); *A*, stand age (years); *M*, stem volume (m^3/ha); *N*, tree density, (1000/ha); *i*, index of biomass component: total (*t*), aboveground (a), roots (r), crowns (c), stems above bark (s), needles (f), branches (b), stem wood (w) ,and stem bark (bk); *X* , dummy variable: for natural pines $X = 0$ and for pine plantations $X = 1$; *PRm*, mean annual precipitation, (mm); *Tm*, January mean annual temperature (°C). Because January mean annual temperature in Northern Eurasia has negative values, the corresponding independent variable is modified to the form $(Tm + 40)$.

Calculation of the coefficients of Equation (1) is performed using a program of common regression analysis, and after correcting on logarithmic transformation according to Baskerville (1972), the coefficients are characterized by R^2 in the range 0.430–0.967 (**Exhibit 3**). All of the regression coefficients for numerical variables in Equation (1) are significant at the level of probability $P_{0.95.}$

The equations are given in an additive form in accordance with the above-mentioned algorithm (Dong et al., 2015) in the sequence shown in the diagram in Exhibit 2. The final form of the transcontinental additive model of component biomass composition of pine forests is shown in the table in **Exhibit 4**.

However, when tabulating model (1), there is a problem, which is that we can know and give only the value of stand age, mean annual precipitation, and mean annual temperature. The remaining two variables *N*, tree density, and *M*, stem volume, can be entered into a table in the form of calculated values obtained by the system of auxiliary recursive equations (Usoltsev et al., 2017). Such equations have a common view:

$$N = \mathrm{f}[A, X(Tm+40), PRm]. \qquad (2)$$

$$M = \mathrm{f}[A, N, X, (Tm+40), PRm] \qquad (3)$$

Equations (2) and (3) are approximated using the original data and are shown in the table in **Exhibit 5**. The results of sequential tabulations of the equations shown in the tables in Exhibits 4 and 5 are unacceptably voluminous; the size of which exceeds the format of a journal article. We took from it the values of component biomass composition of natural pine forests aged 100 years and built graphics showing their dependence upon temperature and precipitation, presented in **Exhibit 6**. As we can see from this exhibit, all of the biomass components vary according to approximately one overall scheme, but in different proportions. The dependence, common to all of the components: in cold climatic zones (Tm = –20°C), any increase in rainfall leads to corresponding decrease in the biomass value, and in warm zones (Tm = 10°C), to an increase in biomass value. Correspondingly, in water-rich areas (PRm = 900 mm), the rise in temperature causes an increase of biomass values, and in arid areas (PRm = 300 mm), in their reductions. These regularities were previously confirmed by other authors on the local level (Glebov & Litvinenko, 1976) and some regional levels (Molchanov, 1976; Polikarpov, & Chebakova, 1982).

For natural and planted stands, the mentioned patterns are the same, but in absolute terms, plantation biomass is higher than natural stands, with the plantation biomass greater than natural for: total, roots, stems, needles and branches, by 16, 18, 11, 2, and 3%, respectively.

The biomass additive model obtained for two-needled pine stands makes it possible to establish any quantitative changes in biomass patterns—in connection with climate change, in particular—with January mean temperatures and mean annual precipitation. Percentage changes in the structure of biomass is related to the ratio of the two climatic indices. In particular, for the central part of European Russia, the Russian Far East, and northeastern China, characterized by mean annual temperature in January of –10°C and mean annual precipitation of 500 mm, any temperature increase of 1°C at a constant level of precipitation increases the biomass of stands aged 100 years by the following: total, roots, stems, needles, and branches by 2.2, 1.8, 2.5, 0.36, and 2.3%, respectively, regardless of the origin of the stands. For the same regions at the same age of pine stands, a precipitation increase of 100 mm with an unchanged mean temperature reduces total, roots, stems, and needles biomass by 5.8, 2.3, 6.5, and 0.3%, respectively, but increases branch biomass by 0.3%.

4 | CONCLUSION

Thus, the first attempt to model changes in the additive component composition of forest stand biomass of two-needled pines, according to Eurasian gradients of the mean January temperature and annual mean precipitation, is made, taking into account regional particularities of age and stand morphology indices. Additivity of component composition means that the total biomass of a tree's components (e.g., stems, branches, foliage, roots), derived from component equations, must be equal to the result obtained using the common equation. In the process of modeling, the database of stand biomass for forest-forming species in Eurasia is used (Usoltsev, 2013). It has been established that in cold climatic zones any increase in rainfall leads to a corresponding decrease in the biomass value and in warm zones, to its increase. In water-rich areas, the rise in temperature causes an increase of biomass values, and in arid areas, it leads to their reductions. This finding has been confirmed by the work of other authors from data they obtained at local and regional levels. The development of such models for basic forest-forming species grown in Eurasia will provide the possibility of predicting changes in the biological productivity of forest cover of Eurasia related to climate change.

EXHIBIT 5 Characteristics of auxiliary recursivse equations for mass-forming indices

Mass-forming indices	Regression coefficients of the model										$adjR^2$
ln N	300.3	$A^{-1.1206}$	–	–	$X^{-0.1297}$	$(Tm{+}40)^{3.3600}$	$(Tm{+}40)^{-0.6335\ln(Tm+40)}$	$PRm^{-1.0095}$	$PRm^{0.0222\ln(PRm)}$	$(Tm{+}40)^{0.0357\ln(PRm)}$	0.555
ln M	97.06	$A^{3.9791}$	$A^{-0.4309(\ln A)}$	$N^{-0.0907}$	$X^{0.2067}$	$(Tm{+}40)^{-10.4134}$	$(Tm{+}40)^{0.2147\ln(Tm+40)}$	$PRm^{3.1242}$	$PRm^{-0.6942\ln(PRm)}$	$(Tm{+}40)^{1.5281\ln(PRm)}$	0.540

Notes: P_i = biomass of ith component in tons per hectare (t/ha); i = index of biomass component: total (t), aboveground (a), roots (r), crowns (c), stems above bark (s), needles (f), branches (b), stem wood (w), and stem bark (bk); A = stand age in years (years); M = stem volume in cubic meters per hectare (m^3/ha); N = tree density, 1,000 per hectare (1,000/ha); X = dummy variable: for natural pines $X = 0$ and for pine plantations $X = 1$; PRm = mean annual precipitation, in millimeters (mm); Tm = January mean annual temperature in degrees Celsius (°C). Because the January mean annual temperature in Northern Eurasia has negative values, the corresponding independent variable is modified to the form ($Tm + 40$).

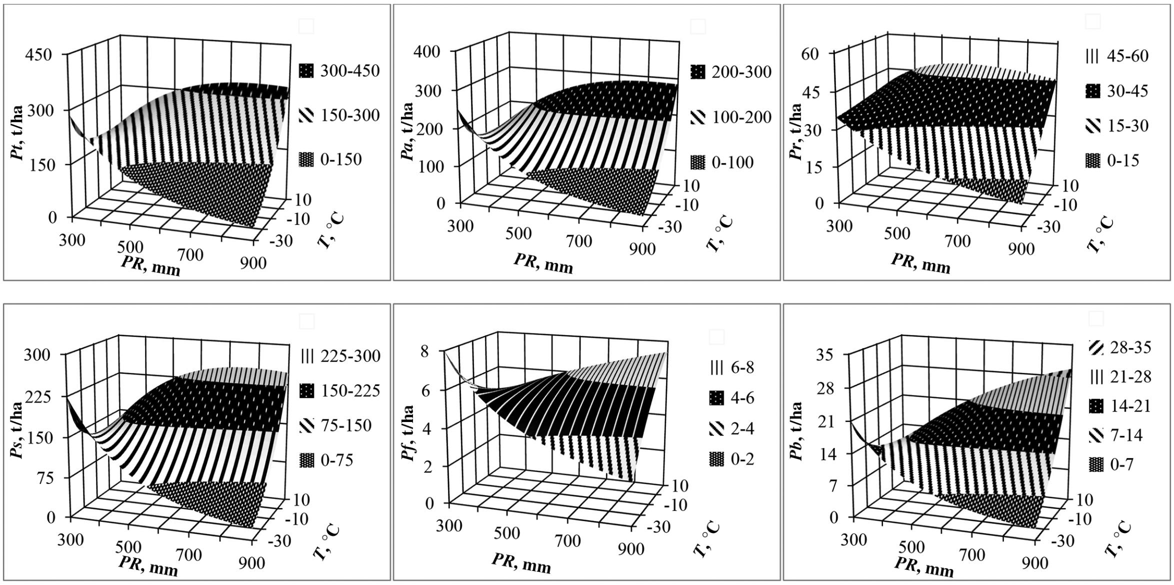

EXHIBIT 6 Dependence of natural pine forest biomass of Eurasia upon the January mean annual temperature (*T*) and precipitation (*PR*). Designations: *Pt*, *Ps*, *Pa*, *Pf*, *Pr*, *Pb*—correspondingly biomass: total, stems, aboveground, needles, roots and branches, t/ha

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REFERENCES

Arrhenius, S. (1896). On the influence of carbonic acid in the air upon the temperature of the ground. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, *41*(251), 237–276. Retrieved from https://www.tandfonline.com/doi/pdf/10.1080/14786449608620846

Baskerville, G. L. (1972). Use of logarithmic regression in the estimation of plant biomass. *Canadian Journal of Forest Research*, *2*(1), 49–53. Retrieved from http://www.nrcresearchpress.com/doi/abs/10.1139/x72-009

Bi, H., Long, Y., Turner, J., Lei, Y., Snowdon, P., Li, Y., … Ximenes, F. (2010). Additive prediction of aboveground biomass for *Pinus radiata* (D. Don) plantations. *Forest Ecology and Management*, *259*(12), 2301–2314. Retrieved from https://www.sciencedirect.com/science/article/pii/S0378112710001490

Budyko, M. I. (1977). *Global ecology* (pp. 328). Moscow, Russia: Mysl (in Russian).

Dong, L., Zhang, L., & Li, F. (2015). A three-step proportional weighting system of nonlinear biomass equations. *Forest Science*, *61*(1), 35–45. Retrieved from https://academic.oup.com/forestscience/article/61/1/35/4584035

Fang, O., Wang, Y., & Shao, X. (2016). The effect of climate on the net primary productivity (NPP) of *Pinus koraiensis* in the Changbai Mountains over the past 50 years. *Trees*, *30*(1), 281–294. Retrieved from https://link.springer.com/article/10.1007/s00468-015-1300-6

Glebov, F. Z., & Litvinenko, V. I. (1976). The dynamics of tree ring width in relation to meteorological indices in different types of wetland forests. *Lesovedenie*, *4*, 56–62 (in Russian).

Kosanic, A., Anderson, K., Harrison, S., Turkington, T., & Bennie, J. (2018). Changes in the geographical distribution of plant species and climatic variables on the West Cornwall Peninsula (South West UK). *PLoS ONE*, *13*(2), e0191021. Retrieved from https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0191021

Laing, J., & Binyamin, J. (2013). Climate change effect on winter temperature and precipitation of yellowknife, northwest territories, Canada from 1943 to 2011. *American Journal of Climate Change*, *2*(04), 275–283. https://doi.org/10.4236/ajcc.2013.24027.

Mäkipää, R., Villén-Peréz, S., Salemaa, M., & Heikkinen, J. (2015). Potential changes in the species' range of geographical distribution. In R. Finland/R. Mäkipää, & T. Kilponen (Eds.), *Towards a new era of forest science in the boreal region: abstracts of the 17th ibfra conference may 24–29, 2015*, . Luonnonvarakeskus (Luke.). Retrieved from https://www.researchgate.net/profile/Sara_Villen-Perez/publication/320234987_Potential_changes_in_the_species%27_range_of_geographical_distribution/links/59d655b20f7e9b42a6a9fbd1/Potential-changes-in-the-species-range-of-geographical-distribution.pdf

Molchanov, A. A (1976). *Dendroclimatic fundamentals of weather forecasts* (pp. 168). Moscow, Russia: Nauka (in Russian).

Ni, J., Zhang, X. S., & Scurlock, J. M. O. (2001). Synthesis and analysis of biomass and net primary productivity in Chinese forests. *Annals of Forest Science*, *58*(4), 351–384. Retrieved from https://www.afs-journal.org/articles/forest/abs/2001/04/ni/ni.html

Polikarpov, N. P., & Chebakova, N. M. (1982). *Evaluation of biological productivity of forest species on the ecological basis. Formation of young-growth stands of coniferous species* (pp. 25–54). Novosibirsk, Russia: Nauka (in Russian).

Schaphoff, S., Reyer, C. P. O., Schepaschenko, D., Gerten, D., & Shvidenko, A. (2016). Tamm review: Observed and projected climate change impacts on Russia's forests and its carbon balance. *Forest Ecology and Management*, *361*, 432–444. Retrieved from https://www.sciencedirect.com/science/article/pii/S0378112715006787

Stegen, J. C., Swenson, N. G., Enquist, B. J., White, E. P., Phillips, O. L., Jørgensen, P. M., … Vargas, P. N. (2011). Variation in above-ground forest biomass across broad climatic gradients. *Global Ecology and Biogeography*, *20*(5), 744–754. Retrieved from https://onlinelibrary.wiley.com/doi/full/10.1111/j.1466-8238.2010.00645.x

Usoltsev, V. A. (2013). *Forest biomass and primary production database for Eurasia. CD-version. The second edition, enlarged and re-harmonized.* Yekaterinburg, Russia: Ural State Forest Engineering University, ISBN

978-5-94984-438-0. Retrieved from http://elar.usfeu.ru/handle/123456789/3059.

Usoltsev, V. A., Voronov, M. P., Shobairi, S. O. R., Dar, J. A., Kolchin, K. V., Chasovskikh, V. P., & Markovskaya, E. V. (2017). Comparative analysis of ordinary and additive models of component composition of tree and forest biomass (on the example of *Picea* sp. and *Abies* sp.). *Eko-Potencial*, *19*(3), 9–31. Retrieved from http://elar.usfeu.ru/bitstream/123456789/6638/1/eko_17-3_01.pdf (in Rusrian).

Zeng, W. S., Duo, H. R., Lei, X. D., Chen, X. Y., Wang, X. J., Pu, Y., & Zou, W. T. (2017). Individual tree biomass equations and growth models sensitive to climate variables for Larix spp. in China. *European Journal of Forest Research*, *136*(2), 233–249. Retrieved from https://link.springer.com/article/10.1007/s10342-017-1024-9

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