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Modelling Forest Stand Biomass and Net Primary Production with the Focus on Additive Models Sensitive to Climate Variables for Two-needled Pines in Eurasia

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Abstract: Modelling forest biomass sensitive to climate change is fulfilled at the levels as forest stands and single-trees, but mostly on a local or regional level, often without regard to the age, morphology of the forest stands and species composition. With this, it does not provide additive component composition, according to which the total of biomass components (stems, branches, needles, and roots), obtained by component equations, would be equal to the value of the biomass obtained by the general equation. The influence of climate change on the biomass of a tree species in the format of additive models for transcontinental hydrothermal gradients has not yet been studied. In the present study, the first attempt is made to model changes in the additive component composition of the stand biomass and NPP of two-needled pines along Trans-Eurasian hydrothermal gradients. In the process of modelling the database of pine stand biomass in a number of 2460 sample plots with the definitions of biomass and 760 plots with the definitions of biomass and annual NPP compiled by the authors, is used.

Keywords: Two-needled pines, biosphere role of forests, forest biomass, allometric model, biological productivity, additive biomass equations, mean January temperature, annual mean precipitation.

Introduction

At the United Nations climate summit in Paris in December 2015, 196 countries committed themselves to reducing CO_2 emissions and preventing annual average temperatures from rising by more than 2°C by the end of the century. Forest ecosystems, as sinks of atmospheric carbon, play an important role in this perspective. Global models examining the relationship between atmospheric CO_2 concentration and air temperature show that, by 2050, a decrease in atmospheric carbon dioxide by 3.5-4 Gt/year will limit the temperature rise to +1.5-2 °C (Meinshausen et al., 2009), i.e. to the threshold above which climate change will have a significant negative impact on biota (IPCC, 2013). This annual decrease of the concentration of CO_2 in the atmosphere can be achieved, in particular, due to the increase of carbon stock in vegetation cover during effective forest management. On the other hand, climate change has a significant impact on the carbon pool and net primary production (NPP) of vegetation, which, in turn, will affect the transformation of the matter cycling and gas exchange in the biosphere (Golubyatnikov and Denisenko, 2009).

In the present study, we make the first attempt to model changes in the additive component composition

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of biomass and NPP of forest ecosystems by Trans-Eurasian gradients of mean January temperatures and mean annual precipitation on the example of two-needled pines (subgenus *Pinus* sp.). In the development of additive systems of equations, preference is given to the principle "from general to particular", in which the equation for the total biomass is "splitted" into additive equations for each component by the method of proportional weighing (Dong et al., 2015).

Materials and Methods

From the database on the biomass and NPP of forests of Eurasia (Usoltsev, 2013) the materials in the amount of 2460 sample plots with the definitions of biomass and 760 plots with the definitions of biomass and annual NPP (t/ha) of phytocenoses of two-needled pines (subgenus *Pinus* sp.) are taken, 86% of that are represented by Scots pine (*Pinus sylvestris* L.) and in a smaller number by *P. tabuliformis* Carr., *P. densiflora* S. et Z., *P. nigra* Arn., *P. pinaster* Ait., *P. pithyusa* (Stev.) Silba, and *P. thunbergii* Parl. Here we take in mind namely phytocenoses, not stands, because we analyze not only the tree stands, but the understorey too. Both are considered in connection with the taxation indices of tree stands.

Each sample plot, at which biomass of forest stands was estimated, is positioned in accordance to mean January temperature isolines (World Weather Maps, 2007) and to mean annual precipitation ones (http://www.mapmost.com/world-precipitation-map/free-world-precipitation-map/), and the initial data matrix is compiled in which the values of biomass components and of stand taxation characteristics are mated with corresponding values of mean temperature and precipitation. The matrix is included then into regression analysis procedure. A schematic map of the isolines of the mean January temperature was used, rather than the mean annual temperature, since warming is most pronounced in the cold half of the year (Golubyatnikov and Denisenko, 2009; Laing and Binyamin, 2013).

A similar procedure was carried out for data on biomass and NPP. Although data on the biomass was three times more than the data on NPP, both are distributed in Eurasian territory with approximately the same density. The biomass data are analyzed in connection with the age, tree density and stem volume as the main mass-determining indices, as well as with the main climatic variables. NPP data are analyzed in connection with the same indices, as well as with the harvest biomass data. General view of the model for biomass:

$$\ln P_i = f\{\ln A, (\ln A)^2, \ln M, \ln N, \ln(Tm+40), [\ln(Tm+40)]^2, \ln PRm, (\ln PRm)^2, [\ln(Tm+40)]\cdot(\ln PRm)\} \quad (1)$$

and general view of the model for NPP:

$$\ln Z_i = f\ \{\ln A,\ (\ln A)^2,\ \ln M,\ \ln N,\ \ln P_i,\ \ln(Tm+40), [\ln(Tm+40)]^2,\ \ln PRm,\ (\ln PRm)^2,\ [\ln(Tm+40)]\cdot(\ln PRm)\} \quad (2)$$

where P_i is biomass of *i*-th component, t/ha; Z_i – annual NPP of *i*-th component, t/ha; *A* – stand age, yrs; *M* – stem volume, m^3/ha; *N* – tree density, 1000/ha; *i* – index of biomass component: all of the phytocenosis, which includes wood storey and understorey (e), understorey, including brushes, the undergrowth, and living grass cover (u), total wood storey (t), aboveground wood storey (a), underground wood storey, or roots (r), tree crown (c), the stem above the bark (s), foliage (f), branches (b), stem wood (w) and stem bark (bk); *PRm* – mean annual precipitation, mm; *Tm* – mean January temperature, °C. Because mean January temperature in northern part of Eurasia has negative values, corresponding independent variable is modified to the form (*Tm*+40). Equations (1) and (2) form a recursive system in which the dependent variable of the first of them is included in the second equation as one of the independent variables.

In contrast to the three-step structure of the disaggregation model of additive system of equations (Dong et al., 2015) shown in Table 1, in our study the total biomass estimated from the initial equation is subdivided into much more biomass component according to the four-step scheme of proportional weighting presented in Figure 1.

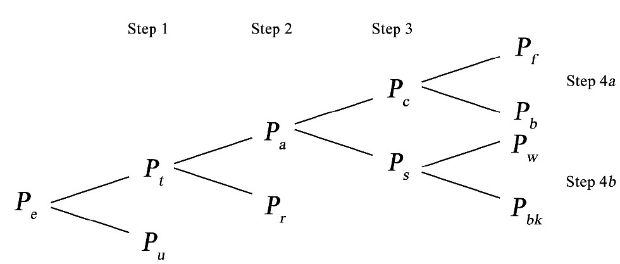

Figure 1: The pattern of disaggregating three-step proportional weighting additive model. Designation: Pe, Pu, Pt, Pr, Pa, Pc, Ps, Pf, Pb, Pw and Pbk are stand biomass respectively: total of the phytocenosis, understorey, total wood storey, underground (roots), aboveground wood storey, tree crown (needles and branches), stems above bark (wood and bark), foliage, branches, stem wood and stem bark correspondingly, t per ha.

Table 1: The structure of the three-step additive model, implemented according to the principle of proportional weighting according to the 122 trees of *Larix gmelinii* (Dong et al., 2015)

Step 1	$P_a = \dfrac{1}{1+\dfrac{a_r D^{b_r} H^{c_r}}{a_a D^{b_a} H^{c_a}}} \times P_t$	$P_c = \dfrac{1}{1+\dfrac{a_s D^{b_s} H^{c_s}}{a_c D^{b_c} H^{c_c}}} \times P_a$
Step 2	$P_f = \dfrac{1}{1+\dfrac{a_b D^{b_b} H^{c_b}}{a_f D^{b_f} H^{c_f}}} \times P_c$	$P_w = \dfrac{1}{1+\dfrac{a_{bk} D^{b_{bk}} H^{c_{bk}}}{a_w D^{b_w} H^{c_w}}} \times P_s$
Step 3a	$P_r = \dfrac{1}{1+\dfrac{a_r D^{b_r} H^{c_r}}{a_a D^{b_a} H^{c_a}}} \times P_t$	$P_s = \dfrac{1}{1+\dfrac{a_c D^{b_c} H^{c_c}}{a_s D^{b_s} H^{c_s}}} \times P_a$
Step 3b	$P_b = \dfrac{1}{1+\dfrac{a_f D^{b_f} H^{c_f}}{a_b D^{b_b} H^{c_b}}} \times P_c$	$P_{bk} = \dfrac{1}{1+\dfrac{a_w D^{b_w} H^{c_w}}{a_{bk} D^{b_{bk}} H^{c_{bk}}}} \times P_s$

Results

The recursive system of the initial regression equations (1) and (2) is calculated by their approximation according to the harvest data using the common regression analysis software. After correcting on logarithmic transformation by Baskerville (1972) and subsequent anti-log procedure, characteristics of equations is given in Tables 2 and 3. All the regression coefficients for numerical variables in equations (1) and (2) are significant at the level of probability $P_{0.95}$ or higher, and the equations are adequate to harvest data.

The equations obtained are modified to additive form according to the above mentioned algorithm (Table 1) in the sequence shown in the scheme (see Figure 1), and the final form of the transcontinental additive model of component composition of biomass and NPP of pine phytocenoses is shown in Tables 4 and 5 respectively.

When tabulating additive models (1) and (2), a problem arises, which consists in the fact that we can specify the indicators of only the forest stand age, temperature and precipitation, but the values of the stem volume and tree density can be entered into the resulting table in the form of calculated values obtained by a system of auxiliary recursive equations.

Such equations have a general form:

$$N = f[A, (Tm{+}40), PRm], \tag{3}$$

$$M = f[A, N, (Tm{+}40), PRm]. \tag{4}$$

The results of calculation (3) and (4) are given in Table 6. The results of tabulating the equations in the sequence (3), (4), (1) and (2) present a rather cumbersome table. We took from it the values of the component composition of biomass and NPP of pine forests for the age of 100 years and built graphs of their dependence upon temperature and precipitation (Figures 2 and 3).

Discussion

Looking at Figures 2 and 3, all the components of biomass and NPP changes are of roughly the same general pattern, but in different proportions. Common to all the components regularity: in the cold zones (*Tm* = –20°C) some precipitation increase leads to a decrease of biomass and NPP, with the exception of the understory, and in the warm ones (*Tm* = 10°C) to their increase, with the exception of the roots. Correspondingly, in wet areas (*PRm* = 900 mm) some increase of temperature causes an increase of biomass and NPP, and in dry areas (*PRm* = 300 mm) it causes their decrease, with the exception of the roots.

A similar general pattern was observed earlier at the local level in the marsh forests of Siberia, where at the maximum amounts of temperature sums above 10°C (2200°C) there is an increase in the radial growth of stems by 30-50% with an increase in precipitation from 400 to 600 mm, and at the minimum amounts of

Table 2: Characteristics of initial equations (1)

Biomass component		*Regression coefficients of equations*									$adjR^2$*	*SE**
Pe	2.16E+02	$A^{0.3563}$	$A^{-0.0328\ln A}$	$M^{0.7819}$	$N^{0.0265}$	$(Tm+40)^{-0.6204}$	$(Tm+40)^{0.1244\ln(Tm+40)}$	$PRm^{-1.4052}$	$PRm^{0.0973\ln PRm}$	$(Tm+40)^{0.0087\ln PRm}$	0.948	1.16
							Step 1					
Pu	1.72E+00	$A^{-2.9440}$	$A^{0.4724\ln A}$	$M^{0.1027}$	$N^{0.2735}$	$(Tm+40)^{-8.6795}$	$(Tm+40)^{-1.0691\ln(Tm+40)}$	$PRm^{4.8803}$	$PRm^{-0.9485\ln PRm}$	$(Tm+40)^{2.4718\ln PRm}$	0.160	2.65
Pt	2.23E+01	$A^{-0.0554}$	$A^{0.0155\ln A}$	$M^{0.8241}$	$N^{0.0108}$	$(Tm+40)^{-1.7963}$	$(Tm+40)^{0.0650\ln(Tm+40)}$	$PRm^{0.0294}$	$PRm^{-0.0688\ln PRm}$	$(Tm+40)^{0.2464\ln PRm}$	0.946	1.18
							Step 2					
Pa	5.37E+01	$A^{-0.2985}$	$A^{0.0438\ln A}$	$M^{0.8276}$	$N^{0.0019}$	$(Tm+40)^{-1.3479}$	$(Tm+40)^{0.0364\ln(Tm+40)}$	$PRm^{-0.4200}$	$PRm^{-0.0147\ln PRm}$	$(Tm+40)^{0.1943\ln PRm}$	0.950	1.19
Pr	4.16E-05	$A^{0.8998}$	$A^{-0.0877\ln A}$	$M^{0.6981}$	$N^{0.0751}$	$(Tm+40)^{2.9861}$	$(Tm+40)^{-0.1301\ln(Tm+40)}$	$PRm^{0.6792}$	$PRm^{0.0331\ln PRm}$	$(Tm+40)^{-0.3208\ln PRm}$	0.798	1.39
							Step 3					
Pc	1.03E+06	$A^{-0.6571}$	$A^{0.0585\ln A}$	$M^{0.5282}$	$N^{-0.0335}$	$(Tm+40)^{-3.2848}$	$(Tm+40)^{-0.0036\ln(Tm+40)}$	$PRm^{-2.3556}$	$PRm^{0.0577\ln PRm}$	$(Tm+40)^{0.5443\ln PRm}$	0.620	1.39
Ps	8.92E-01	$A^{0.2960}$	$A^{-0.0226\ln A}$	$M^{0.9250}$	$N^{0.0238}$	$(Tm+40)^{-0.9201}$	$(Tm+40)^{0.1253\ln(Tm+40)}$	$PRm^{0.0278}$	$PRm^{-0.0092\ln PRm}$	$(Tm+40)^{0.0339\ln PRm}$	0.964	1.19
							Step 4a					
Pf	3.14E+05	$A^{-0.6042}$	$A^{0.0327\ln A}$	$M^{0.4402}$	$N^{0.0320}$	$(Tm+40)^{-1.0199}$	$(Tm+40)^{-0.0085\ln(Tm+40)}$	$PRm^{-3.2418}$	$PRm^{0.2328\ln PRm}$	$(Tm+40)^{0.1567\ln PRm}$	0.427	1.43
Pb	8.51E+04	$A^{-0.4542}$	$A^{0.0394\ln A}$	$M^{0.5820}$	$N^{-0.0837}$	$(Tm+40)^{-4.9570}$	$(Tm+40)^{0.0232\ln(Tm+40)}$	$PRm^{-1.1153}$	$PRm^{-0.1073\ln PRm}$	$(Tm+40)^{0.7985\ln PRm}$	0.651	1.47
							Step 4b					
Pw	7.78E+01	$A^{0.5934}$	$A^{-0.0606\ln A}$	$M^{0.9300}$	$N^{-0.0002}$	$(Tm+40)^{1.4078}$	$(Tm+40)^{-0.1667\ln(Tm+40)}$	$PRm^{-2.9687}$	$PRm^{0.2746\ln PRm}$	$(Tm+40)^{-0.0631\ln PRm}$	0.965	1.17
Pbk	1.54E+21	$A^{0.5314}$	$A^{-0.0397\ln A}$	$M^{0.6576}$	$N^{0.1786}$	$(Tm+40)^{-6.5107}$	$(Tm+40)^{0.6838\ln(Tm+40)}$	$PRm^{-13.6022}$	$PRm^{1.0254\ln PRm}$	$(Tm+40)^{0.3465\ln PRm}$	0.783	1.36

* $adjR^2$ – Determination coefficient adjusted for the number of variables; *SE* – Standard error of the equation in the original dimension P_i (t/ha).

Table 3: Characteristics of initial equations (2)

NPP component	*Regression coefficients of equations*										*adj*R^2	*SE*
Z_e	6.99E+04	$A^{-0.4898}$	$M^{-0.2614}$	$N^{0.0465}$	$P_e^{1.0163}$	$(Tm+40)^{-3.7635}$	$(Tm+40)^{-0.7310\ln(Tm+40)}$	$PRm^{-1.6257}$	$PRm^{-0.1917\ln PRm}$	$(Tm+40)^{1.3227\ln PRm}$	0.803	1.27
Step 1												
Z_u	2.47E-03	$A^{0.0357}$	$M^{-0.0375}$	$N^{-0.0489}$	$P_u^{0.8072}$	$(Tm+40)^{-7.2010}$	$(Tm+40)^{-1.6232\ln(Tm+40)}$	$PRm^{4.6516}$	$PRm^{-0.9806\ln PRm}$	$(Tm+40)^{2.7017\ln PRm}$	0.679	1.80
Z_t	2.87E+09	$A^{-0.7220}$	$M^{-0.2197}$	$N^{0.0271}$	$P_t^{1.0385}$	$(Tm+40)^{3.0752}$	$(Tm+40)^{-0.5067\ln(Tm+40)}$	$PRm^{-8.0780}$	$PRm^{0.6029\ln PRm}$	$(Tm+40)^{0.0736\ln PRm}$	0.782	1.38
Step 2												
Z_a	1.45E-01	$A^{-0.7261}$	$M^{-0.0231}$	$N^{0.0643}$	$P_a^{0.7868}$	$(Tm+40)^{-3.9381}$	$(Tm+40)^{-0.8331\ln(Tm+40)}$	$PRm^{2.7315}$	$PRm^{-0.5783\ln PRm}$	$(Tm+40)^{1.4865\ln PRm}$	0.779	1.34
Z_r	2.38E+08	$A^{-1.0781}$	$M^{-0.3977}$	$N^{-0.0257}$	$P_r^{1.4422}$	$(Tm+40)^{4.5807}$	$(Tm+40)^{0.2165\ln(Tm+40)}$	$PRm^{-7.4801}$	$PRm^{0.7766\ln PRm}$	$(Tm+40)^{-0.8864\ln PRm}$	0.684	1.73
Step 3												
Z_c	4.11E+00	$A^{-0.3770}$	$M^{0.0795}$	$N^{0.0753}$	$P_c^{0.8137}$	$(Tm+40)^{-6.3935}$	$(Tm+40)^{-0.9736\ln(Tm+40)}$	$PRm^{2.7095}$	$PRm^{-0.7123\ln PRm}$	$(Tm+40)^{1.9891\ln PRm}$	0.695	1.42
Z_s	3.89E-06	$A^{-0.9823}$	$M^{-0.1462}$	$N^{0.0697}$	$P_s^{0.9767}$	$(Tm+40)^{-1.5701}$	$(Tm+40)^{-1.1014\ln(Tm+40)}$	$PRm^{4.8693}$	$PRm^{-0.7107\ln PRm}$	$(Tm+40)^{1.3768\ln PRm}$	0.743	1.46
Step 4a												
Z_f	1.97E+07	$A^{-0.0682}$	$M^{0.0484}$	$N^{0.0227}$	$P_f^{0.9299}$	$(Tm+40)^{-6.4039}$	$(Tm+40)^{-1.0665\ln(Tm+40)}$	$PRm^{-2.4802}$	$PRm^{-0.3153\ln PRm}$	$(Tm+40)^{2.0776\ln PRm}$	0.666	1.49
Z_b	6.40E-17	$A^{-0.9372}$	$M^{0.3179}$	$N^{0.1571}$	$P_b^{0.6652}$	$(Tm+40)^{-6.2458}$	$(Tm+40)^{-1.2044\ln(Tm+40)}$	$PRm^{15.0746}$	$PRm^{-1.7309\ln PRm}$	$(Tm+40)^{2.1732\ln PRm}$	0.605	1.78
Step 4b												
Z_w	5.00E+20	$A^{-1.0054}$	$M^{-0.0080}$	$N^{0.0930}$	$P_w^{0.8356}$	$(Tm+40)^{-8.4182}$	$(Tm+40)^{-8.6520\ln(Tm+40)}$	$PRm^{-11.0953}$	$PRm^{-1.9443\ln PRm}$	$(Tm+40)^{10.7133\ln PRm}$	0.571	1.64
Z_{bk}	2.83E+18	$A^{-0.6304}$	$M^{0.0282}$	$N^{0.2659}$	$P_{bk}^{0.7255}$	$(Tm+40)^{-49.9360}$	$(Tm+40)^{2.6203\ln(Tm+40)}$	$PRm^{13.0169}$	$PRm^{-2.3479\ln PRm}$	$(Tm+40)^{5.0254\ln PRm}$	0.551	1.72

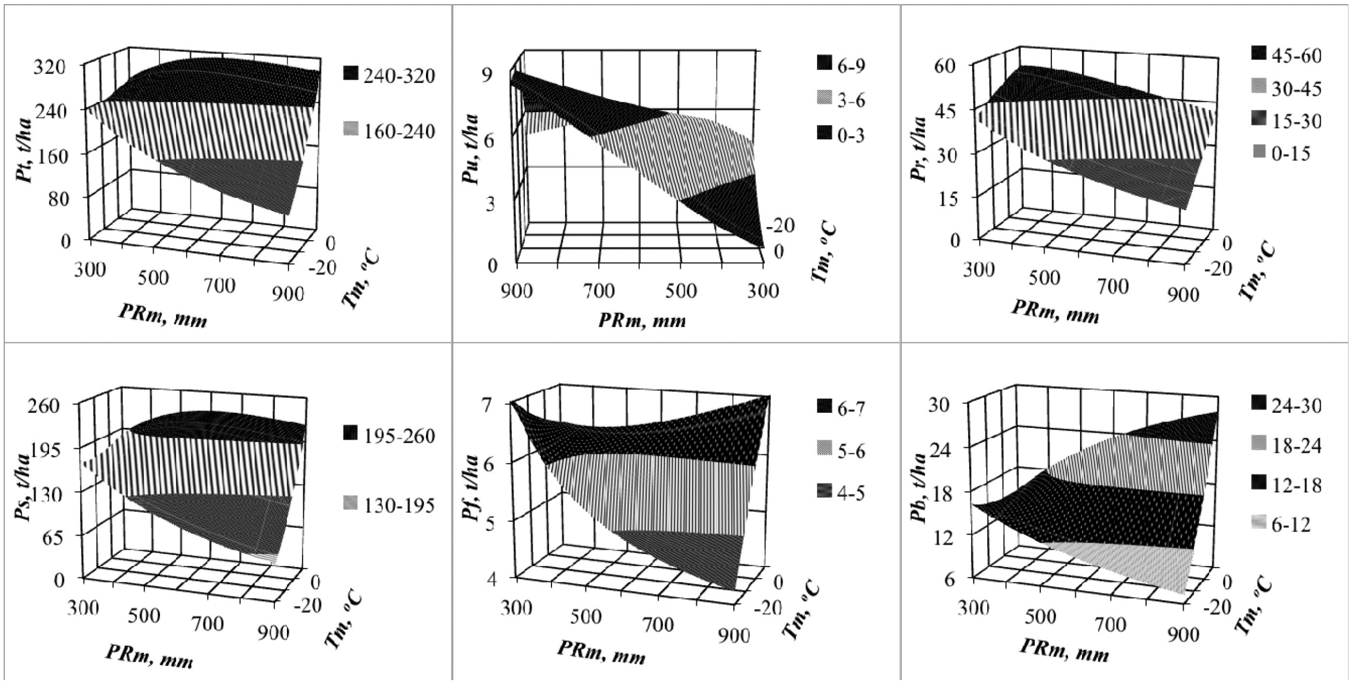

Figure 2: Dependence of pine phytocenoses biomass of Eurasia upon the average January temperature (*Tm*) and average annual precipitation (*PRm*). Designations: *Pt, Pu, Pr, Ps, Pf* and *Pb* are respectively biomass of: total wood storey, understorey, underground storey (roots), stems (wood and bark), foliage and branches, t/ha.

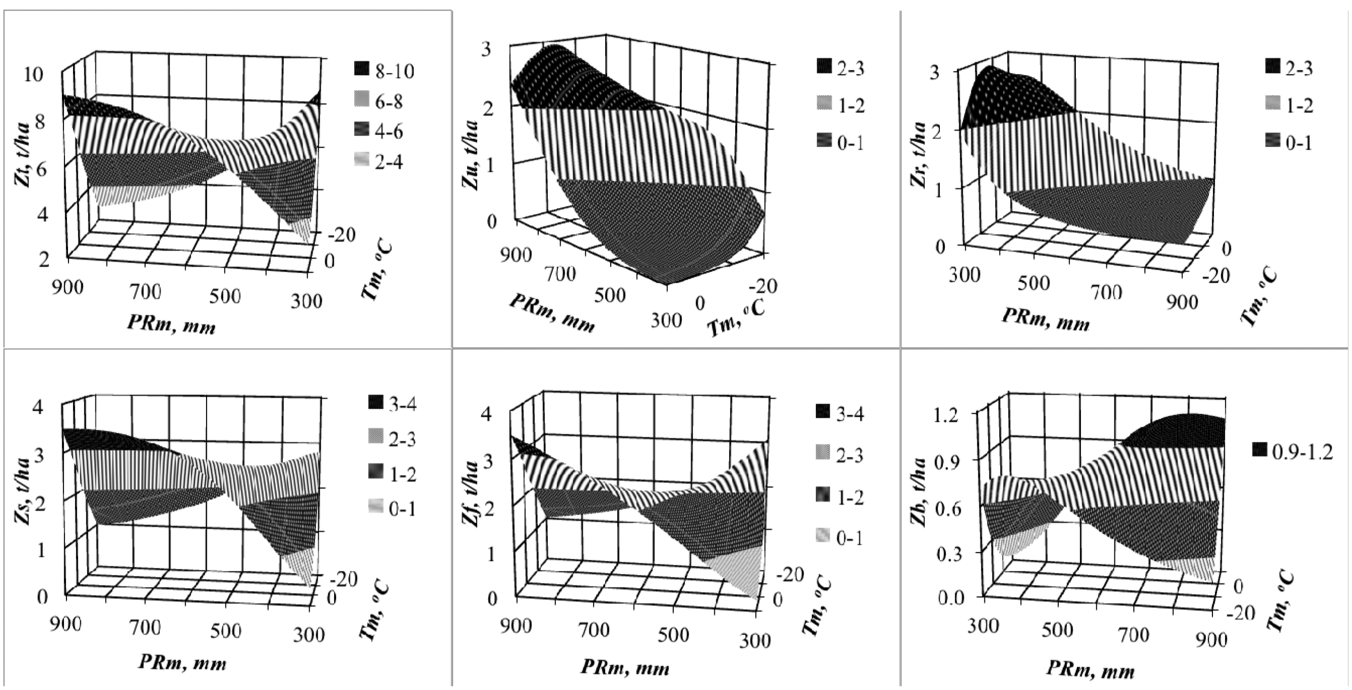

Figure 3: Dependence of pine phytocenoses NPP of Eurasia upon the average January temperature (*Tm*) and average annual precipitation (*PRm*). Designations see Figure 2.

temperature sums (1600°C) the radial growth is reduced by 4-9% with an increase in precipitation in the same range. Correspondingly, at the level of precipitation of 400 mm the radial growth is reduced by 14-20% with an increase in the sum of temperatures from 1600 to 2200°C, and it increases by 14-33% in the same temperature range at the level of precipitation of 600 mm (Glebov and Litvinenko, 1976).

Table 4: Four-step additive model of biomass component composition of pine forest stands designed according to scheme of proportional weighting

$$Pe = 1+2.16E{+}02\ A^{0.3563}\ A^{-0.0328\ \ln A}\ M^{0.7819}\ N^{0.0265}\ (Tm+40)^{-0.6204}\ (Tm+40)^{0.1244(Tm+40)}\ PRm^{-1.4052}\ PRm^{0.0973\ \ln PRm}\ (Tm+40)^{0.0087\ \ln PRm}$$

Step 1

$$Pu = \frac{1}{1+1.29E{+}01\ A^{2.8886}\ A^{-0.4569\ \ln A}\ M^{0.7215}\ N^{-0.2627}\ (Tm+40)^{6.8832}\ (Tm+40)^{1.1341\ \ln(Tm+40)}\ PRm^{-4.8509}\ PRm^{0.8796\ \ln PRm}\ (Tm+40)^{-2.2254\ \ln PRm}} \times Pe$$

$$Pt = \frac{1}{1+7.73E{-}02\ A^{-2.8886}\ A^{0.4569\ \ln A}\ M^{-0.7215}\ N^{0.2627}\ (Tm+40)^{-6.8832}\ (Tm+40)^{-1.1341\ \ln(Tm+40)}\ PRm^{4.8509}\ PRm^{-0.8796\ \ln PRm}\ (Tm+40)^{2.2254\ \ln PRm}} \times Pe$$

Step 2

$$Pa = \frac{1}{1+7.74E{-}07\ A^{1.1983}\ A^{-0.1315\ \ln A}\ M^{-0.1295}\ N^{0.0732}\ (Tm+40)^{4.3340}\ (Tm+40)^{-0.1665\ \ln(Tm+40)}\ PRm^{1.0992}\ PRm^{0.0478\ \ln PRm}\ (Tm+40)^{-0.5152\ \ln PRm}} \times Pt$$

$$Pr = \frac{1}{1+1.29E{+}06\ A^{-1.1983}\ A^{0.1315\ \ln A}\ M^{0.1295}\ N^{-0.0732}\ (Tm+40)^{-4.3340}\ (Tm+40)^{0.1665\ \ln(Tm+40)}\ PRm^{-1.0992}\ PRm^{-0.0478\ \ln PRm}\ (Tm+40)^{0.5152\ \ln PRm}} \times Pt$$

Step 3

$$Pc = \frac{1}{1+8.63E{-}07\ A^{0.9531}\ A^{-0.0811\ \ln A}\ M^{0.3968}\ N^{0.0573}\ (Tm+40)^{2.3647}\ (Tm+40)^{0.1290\ \ln(Tm+40)}\ PRm^{2.3835}\ PRm^{-0.0669\ \ln PRm}\ (Tm+40)^{-0.5104\ \ln PRm}} \times Pa$$

$$Ps = \frac{1}{1+1.16E{+}06\ A^{-0.9531}\ A^{0.0811\ \ln A}\ M^{-0.3968}\ N^{-0.0573}\ (Tm+40)^{-2.3647}\ (Tm+40)^{-0.1290\ \ln(Tm+40)}\ PRm^{-2.3835}\ PRm^{0.0669\ \ln PRm}\ (Tm+40)^{0.5104\ \ln PRm}} \times Pa$$

Step 4*a*

$$Pf = \frac{1}{1+2.71E{-}01\ A^{0.1499}\ A^{0.0067\ \ln A}\ M^{0.1418}\ N^{-0.1157}\ (Tm+40)^{-3.9371}\ (Tm+40)^{0.0317\ \ln(Tm+40)}\ PRm^{2.1265}\ PRm^{-0.3401\ \ln PRm}\ (Tm+40)^{0.6418\ \ln PRm}} \times Pc$$

$$Pb = \frac{1}{1+3.70E{+}00\ A^{-0.1499}\ A^{-0.0067\ \ln A}\ M^{-0.1418}\ N^{0.1157}\ (Tm+40)^{3.9371}\ (Tm+40)^{-0.0317\ \ln(Tm+40)}\ PRm^{-2.1265}\ PRm^{0.3401\ \ln PRm}\ (Tm+40)^{-0.6418\ \ln PRm}} \times Pc$$

Step 4*b*

$$Pw = \frac{1}{1+1.98E{+}19\ A^{-0.0619}\ A^{0.0209\ \ln A}\ M^{-0.2724}\ N^{0.1788}\ (Tm+40)^{-7.9185}\ (Tm+40)^{0.8505\ \ln(Tm+40)}\ PRm^{-10.6335}\ PRm^{0.7508\ \ln PRm}\ (Tm+40)^{0.4096\ \ln PRm}} \times Ps$$

$$Pbk = \frac{1}{1+5.05E{-}20\ A^{0.0619}\ A^{-0.0209\ \ln A}\ M^{0.2724}\ N^{-0.1788}\ (Tm+40)^{7.9185}\ (Tm+40)^{-0.8505\ \ln(Tm+40)}\ PRm^{10.6335}\ PRm^{-0.7508\ \ln PRm}\ (Tm+40)^{-0.4096\ \ln PRm}} \times Ps$$

Table 5: Four-step additive model of NPP component composition of pine forest stands designed according to scheme of proportional weighting

$$Ze = 6.99E{+}04\, A^{-0.4898} M^{-0.2614} N^{0.0465} Pe^{1.0163} (Tm+40)^{-3.7635} (Tm+40)^{-0.7310 \ln(Tm+40)} PRm^{-1.6257} PRm^{-0.1917 \ln PRm} (Tm+40)^{1.3227 \ln PRm}$$

Step 1

$$Zu = \frac{1}{1.16E{+}12\, A^{-0.7577} M^{-0.1822} N^{0.0760} Pu^{0.2314} (Tm+40)^{10.2762} (Tm+40)^{1.1165 \ln(Tm+40)} PRm^{-12.7295} PRm^{1.5835 \ln PRm} (Tm+40)^{-2.6281 \ln PRm}} \times Ze$$

$$Zt = \frac{1}{8.60E{-}13\, A^{0.7577} M^{0.1822} N^{-0.0760} Pt^{-0.2314} (Tm+40)^{-10.2762} (Tm+40)^{-1.1165 \ln(Tm+40)} PRm^{12.7295} PRm^{-1.5835 \ln PRm} (Tm+40)^{2.6281 \ln PRm}} \times Ze$$

Step 2

$$Za = \frac{1}{1.64E{+}09\, A^{-0.3521} M^{-0.3747} N^{-0.0900} Pa^{0.6553} (Tm+40)^{8.5188} (Tm+40)^{1.0496 \ln(Tm+40)} PRm^{-10.2116} PRm^{1.3548 \ln PRm} (Tm+40)^{-2.3729 \ln PRm}} \times Zt$$

$$Zr = \frac{1}{6.08E{-}10\, A^{0.3521} M^{0.3747} N^{0.0900} Pr^{-0.6553} (Tm+40)^{-8.5188} (Tm+40)^{-1.0496 \ln(Tm+40)} PRm^{10.2116} PRm^{-1.3548 \ln PRm} (Tm+40)^{2.3729 \ln PRm}} \times Zt$$

Step 3

$$Zc = \frac{1}{9.48E{-}07\, A^{-0.6053} M^{-0.2257} N^{-0.0057} Pc^{0.1631} (Tm+40)^{4.8234} (Tm+40)^{-0.1278 \ln(Tm+40)} PRm^{2.1598} PRm^{0.0016 \ln PRm} (Tm+40)^{-0.6123 \ln PRm}} \times Za$$

$$Zs = \frac{1}{1.06E{+}06\, A^{0.6053} M^{0.2257} N^{0.0057} Ps^{-0.1631} (Tm+40)^{-4.8234} (Tm+40)^{0.1278 \ln(Tm+40)} PRm^{-2.1598} PRm^{-0.0016 \ln PRm} (Tm+40)^{0.6123 \ln PRm}} \times Za$$

Step 4*a*

$$Zf = \frac{1}{3.25E{-}24\, A^{-0.8689} M^{0.2695} N^{0.1344} Pf^{-0.2648} (Tm+40)^{0.1581} (Tm+40)^{-0.1379 \ln(Tm+40)} PRm^{17.5548} PRm^{-1.4156 \ln PRm} (Tm+40)^{0.0956 \ln PRm}} \times Zc$$

$$Zb = \frac{1}{3.07E{+}23\, A^{0.8689} M^{-0.2695} N^{-0.1344} Pb^{0.2648} (Tm+40)^{-0.1581} (Tm+40)^{0.1379 \ln(Tm+40)} PRm^{-17.5548} PRm^{1.4156 \ln PRm} (Tm+40)^{-0.0956 \ln PRm}} \times Zc$$

Step 4*b*

$$Zw = \frac{1}{5.66E{-}03\, A^{0.3750} M^{0.0362} N^{0.1729} Pw^{-0.1101} (Tm+40)^{-41.5178} (Tm+40)^{11.2722 \ln(Tm+40)} PRm^{24.1122} PRm^{-0.4036 \ln PRm} (Tm+40)^{-5.6879 \ln PRm}} \times Zs$$

$$Zbk = \frac{1}{1.77E{+}02\, A^{-0.3750} M^{-0.0362} N^{-0.1729} Pbk^{0.1101} (Tm+40)^{41.5178} (Tm+40)^{-11.2722 \ln(Tm+40)} PRm^{-24.1122} PRm^{0.4036 \ln PRm} (Tm+40)^{5.6879 \ln PRm}} \times Zs$$

Table 6: Characteristics of the recursive system of auxiliary equations for mass-forming indices

Mass-forming indices	*Regression coefficients of equations*									*adjR²*	*SE*
N	2.04E+01	$A^{-1.0921}$	-	-	$(Tm+40)^{2.5724}$	$(Tm+40)^{-0.5426 \ln(Tm+40)}$	$PRm^{0.1734}$	$PRm^{-0.0809 \ln PRm}$	$(Tm+40)^{0.0740 \ln PRm}$	0.553	2.10
M	4.51E+03	$A^{3.8412}$	$A^{-0.4196 \ln A}$	$N^{-0.0993}$	$(Tm+40)^{-8.8996}$	$(Tm+40)^{0.0411 \ln(Tm+40)}$	$PRm^{1.3158}$	$PRm^{-0.5326 \ln PRm}$	$(Tm+40)^{1.4540 \ln PRm}$	0.533	1.91

In the mountains of southern Siberia the site index of Siberian pine, fir, larch and Scots pine forests increases from Va to I class when the temperature sum above 10°C rises from 400°C to 1600°C, and it decreases from I to Va class when dryness index (after Budyko, 1984) changes from 1.0 to 0.2. More informative was the correlation analysis of the site index with both climatic factors simultaneously: "If in cold zones (the sum of temperatures below 800°C) the thermic factor is a determining the productivity level, since forest productivity changes in the direction of change of temperature sums, then in warm zones (the sum of temperatures above 800°) the change of the site index occurs along the gradient of the dryness index, which confirms the leading role of the relative moisture factor" (Polikarpov and Chebakova, 1982).

According to the results obtained by Molchanov (1976), in the North of Eurasia the greatest influence on the growth of the annual tree ring is the air temperature, and in the conditions of the southern forest-steppe the dominant role is played by precipitation.

Thus, our results on changes in the structure of biomass and NPP of pine phytocenoses in two climatic gradients mainly confirm the regularities previously established by other researchers at the local and regional levels.

Conclusions

This is the first attempt of modelling changes in additive component composition of biomass and net primary production (NPP) of plant communities two-needled pines on the Trans-Eurasian hydrothermal gradients based on regional peculiarities of age and morphology of the forests. Cold climatic zones precipitation increase leads to a decrease in biomass and NPP, and in warm ones its increase. Similarly in wet areas increase of temperature causes an increase of biomass and NPP compared to dry areas. The deviations from the mentioned general pattern are observed in the biomass and NPP of roots. The developed models for basic forest species grown in Eurasia thus gives possibility to predict changes in the biological productivity of Eurasian forest in the climate change scenarios.

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