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Feedback Modelling of Natural Stand and Plantation Biomass to Changes in Climatic Factors (Temperatures and Precipitation): A Special Case for Two-needles Pines in Eurasia

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Abstract: A comparative discussion on advantages and disadvantages of natural stands and plantations, including their productivity and resistance, began from the moment of first forest plantings and continues to this day. In the context, progressive replacement of natural forests by plantations, the question of how that will change the carbon storage capacity of forest cover when replacing natural forests with planted ones in a changing climate becomes extremely relevant. This article presents the first attempt to answer this question at the transcontinental level on a special case for two-needles pine trees (subgenus *Pinus* L.). The research was carried out using the database compiled by the authors on the tree biomass allocation structure for major tree species of Eurasia, in particular, the 1880 and 1967 data of naturally regenerated and planted sample pine trees, respectively. Multi-factor regression models were calculated after combining the matrix of initial data on the structure of tree biomass with the mean temperature of January and mean annual precipitation; their adequacy indices allow us to consider them reproducible. It is found that the aboveground biomass of equal-sized and equal-aged natural and planted trees increases with the rise in the temperature in the month of January and annual precipitation. This pattern is only partially valid for the branches' biomass. Iit has a specific character for the foliage one. The biomass of all components of planted trees is higher than that of natural trees, but the percentage excess varies among different components and depends on the level of January's temperature, but does not depend at all on the level of annual precipitation. The uncertainties of estimations, as well as the nature of the obtained regularities, are discussed in the text.

Keywords: Two-needles pine trees; Natural stands and plantations; Regression models; Biomass equations; Mean January temperature; Annual precipitation.

Introduction

The current climate makes it increasingly important to assess the response of forest biomass to the changes in the environment, which, in turn, determines the possibility of climate stabilisation by reducing atmospheric CO_2. Climate change projections have been linked to significant increases in water deficits and natural disturbance regimes in forest ecosystems across many parts of the world during the 21st century

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(Clark et al., 2016). Climate change may lead to substantial drought on large territories of Siberian forest ecosystems, and increase global warming (Shvidenko et al., 2013). This is compounded by anthropogenic pressure and lack of governance in Russia (Onuchin et al., 2009).

Some researchers have argued that by increasing the total area, the world's forests could store around one-quarter of the atmospheric CO_2 necessary to limit global warming upto 1.5°C above pre-industrial levels (Lewis et al., 2019). Nevertheless, others consider it almost unreal (Boysen et al., 2017). A study by Sedjo and Solomon (1989) indicates that the current annual increase in atmospheric carbon could be sequestered for about 30 years in approximately 465 million ha of plantation forests. As Ciesla (1995) believes, this would require increasing more than 10% of the current area of forests present on earth. It would also represent increasing more than four times the present plantation area globally, but there are no suitable areas on such scale.

Mackey (2014) states: "Half the world's natural forests have already been cleared. Only about a quarter of what is left retains its carbon-carrying capacity". The planet's natural forests are slowly decreasing by 6-13 million ha annually (FAO, 2006; Kirilenko and Sedjo, 2007), and are often replaced by artificial ones (Niskanen, 2000). This accounts for 4% of the world's forests, which is growing continuously (Brockerhoff et al., 2008; Pawson et al., 2013). It is necessary to know how this substitution can affect the change in the biomass structure of the artificial forests under the influence of climate shifts and, accordingly, their carbon-depositing capacity and resilience to climate change (Pawson et al., 2013).

Because climate change affects the natural environment, established as a result of the long-term evolution of vegetation (Emanuel et al., 1985; Kobak, Kondrasheva, 1992; Mäkipää et al., 2015; Kosanic et al., 2018; Roberts, 2019). This certainly causes changes in plant cover productivity (Kobak and Kondrasheva, 1985; Dulamsuren et al., 2013; Bennett et al., 2016; Schaphoff et al., 2016; Fang et al., 2016; Duan et al., 2018), as well as the accelerated successional changes and dominate species in their process (Bolte et al., 2014). To predict the impact of climate change on forest productivity, it is necessary to know the relationship of forest biomass with climate indices (Stegen et al., 2011; Dymond et al., 2016).

Since it is well known that man-made forests have low environmental sustainability, especially near the ecological limits of the species distribution, a large number of studies have been dedicated to analyse the causes for low sustainability (Maksimov, 1944; Karpov, 1950; Berezyuk, 1959; Godnev, 1965; Nevzorov, 1970; Godnev and Nevzorov, 1970; Antsiferov et al., 1971; Mironov, 1977; Sidorov et al., 1978; Makarenko and Biryukova, 1982; Biryukova and Makarenko, 1983; Biryukova and Biryukov, 1984; Usoltsev, 1985; Yuodvalkis and Jonikas, 1985; Verzunov, 1987; Yang et al., 2004; Li et al., 2011; Maurer and Pinchuk, 2014; Navarro-Cerrillo et al., 2018). On the other hand, man-made forests, as compared to natural forests, fit better for the concept of adaptive forest management (Nabuurs et al., 2007). Today, in the context of increasing anthropogenic pressure and climate change, it is important to know all the advantages and disadvantages of both natural stands and plantations in terms of biological productivity and their ability to mitigate climate change.

Natural and artificial stands differ in many aspects: biomass and production component increase in a chronosequence (Jordan and Farnworth, 1982; Usoltsev, 1985, 1988; Gabeev, 1990; Usoltsev and Vanclay, 1993, 1995; Usoltsev et al., 1994), single-tree biomass allometry (Usoltsev, 2016; Durkaya et al., 2016) involving its additive case (Usoltsev et al., 2017), resistance to droughts (Khonin, 1974; Makarenko and Biryukova, 1982; Biryukova and Makarenko, 1983; Usoltsev, 1985; Verzunov, 1987; Usoltsev and Vanclay, 1993, 1995; Usoltsev et al., 1994; Bell et al., 2015; Navarro-Cerrillo et al., 2018; Rodriguez-Vallejo and Navarro-Cerrillo, 2019), fine root distribution, seasonal pattern and production (Yang et al., 2004), characteristics of the macrostructure of wood (Melekhov et al., 2003; Antonov, 2007), technological properties of wood, in particular, sliced veneer quality (Tekpetey et al., 2014), tree genetic similarity (Gauli et al., 2009), variability of morphological markers of the reproductive organs (Mazhula, 2018), species diversity (Sobuj, 2011), species composition, individual tree distribution, and competitive relationships (Gao et al., 2014), pollinator abundance in crop fields (Taki et al., 2011), reaction to a mass outbreak of parasites (Grabenweger et al., 2005), biomass structure in air pollution gradients near copper plants (Yusupov et al., 1997; Usoltsev et al., 2012), dynamic structural stand density diagrams (Usoltsev and Vanclay, 1995; Stankova and Diéguez-Aranda, 2020).

Discussions on the production advantages of natural and artificial forests were initiated from the first forest plantation and continuesuntil now. Numerous studies proved the presence of higher production indices of plantations as compared to natural stands. (Rubtsov et al., 1976; Stage et al., 1988; Gabeev, 1990; Danchenko et al., 1991; Chernov, 2001; Antonov, 2007; Lugansky and Shipitsina, 2008; Merzlenko, 2017; Usoltsev et al., 2017). Nevertheless, pieces of evidence were found for greater biological productivity of plantations at a young age (Zolotukhin, 1966; Makarenko and Biryukova, 1982; Jordan and Farnworth, 1982; Polyakov et al., 1986; Romanov et al., 2014). The plantations also showed greater biological productivity of natural forests as compared to planted forests in Southeast China (Liu et al., 2016). Climate change increases this uncertainty, and a comparative analysis of possible changes in the biomass of natural stands and plantations, as a result of climate shifts, becomes even more relevant.

Recently, a comparative analysis for the accuracy of different methods for determining the biological productivity of some tree species was completed. The results showed that allometric models designed at a tree scale gave a smaller prediction error as compared to models performed at the forest stand scale (Zeng et al., 2018). Such single-tree allometric models for mixed stands are particularly relevant. A climate-sensitive aboveground biomass model led to a higher prediction accuracy of tree biomass than those without climatic variables for three larch species (Fu et al., 2017). A study was performed on the sensitivity of allometric models for aboveground and belowground biomass of larches in China to changes in hydrothermal conditions. It revealed that the increase in mean annual temperature by 1°C leads to an increase in aboveground biomass of trees to 0.87% and reduce belowground biomass to 2.26%. The increase in average annual precipitation by 100 mm causes a decrease in aboveground and belowground biomasses at 1.52 and 1.09%, respectively (Zeng et al., 2017). In such studies, the task is to extract the climatic component (climate signals) from the residual dispersion of a model calculated. To know about climatic factors and make them "recoverable" from this "information noise", it is necessary to consider the tree in the model, in addition to the stem diameter and height, which is an important factor for determining the structure of tree biomass (Nikitin, 1965; Kazaryan, 1966; Usoltsev, 1972; Tsel'niker, 1994; Vanninen et al., 1996; Bond-Lamberty et al., 2002; Genet et al., 2011; Fatemi et al., 2011; Ochał et al, 2013; Qiu et al., 2018), as well as climate sensitivity (Carrer and Urbinati, 2004; Yu et al., 2008).

In our study, the first attempt is to compare the changes in the component of tree biomass composition of two-needles pines of natural and artificial stands by trans-Eurasian hydrothermal gradients using the unique Eurasian database of, harvest data on single tree biomass compiled by V.A. Usoltsev (2016). As climatic variables are geographically known, it can be expected that the improvement of allometric biomass models, considering not only the age, height and stem diameter as independent variables and also climate indices, will allow to identify and quantify some changes in the biomass structure of equal-aged and equal-sized trees related to climate variables and will provide climate-sensitivity of such models (Forrester et al., 2017; Zeng et al., 2017; Fu et al., 2017). The implementation of our intention is encouraged by the result of Rodriguez-Vallejo and Navarro-Cerrillo (2019) showed that climatic variables (temperature and precipitation), as well as site and soil conditions, cause differences in the forest cover change between natural and planted stands.

Material and Methods

From the mentioned database, the data for the subgenus *Pinus* L. aboveground biomass in a number of 2628 sample trees, including 1980 and 1967 for natural and artificial stands respectively, were taken (Table 1). There were only 370 definitions for root biomass in the database. The subgenus *Pinus* L. is mainly represented by the Scots pine (*Pinus sylvestris* L.) (86 % of the total data) and in a smaller number by species *P. tabuliformis* Carr., *P. massoniana* Lamb., *P. densiflora* S. et Z., *P. thunbergii* Parl.

The joint analysis of different species is caused by the impossibility of growing the same tree species throughout Eurasia. As a result of which their areas within the genus are confined to certain ecoregions. These are substitutive or vicariate species that arose in cases of geologically long-standing separation of a once-continuous area under influence of climate traits (Tolmachev, 1962) or as a result of climate-related morphogenesis (Chernyshev, 1974).

Sample plots for tree biomass estimations are plotted against the mean January temperature (Figure 1) and mean annual precipitation (Figure 2). The use of evapotranspiration as a combined index in the assessment of tree production is useless since it explains only 24% of its variability compared to 42%, which shows its relation to mean annual precipitation, and compared to 31%, which provides the relation to mean annual temperature (Ni et al., 2001). Therefore, the use of temperature and precipitation indices taken from World Weather Maps (2007) are preferable as one of the most informative climatic factors.

Table 1: Distribution of the 2628 sample trees by species, countries, regions and mensuration indices

Region	*Species of the subgenus Pinus L.*	*Ranges:*			*Number of sample trees*
		Age, yrs	*DBH, cm*	*Height, m*	
Trees in Natural Forest					
West Europa	*P. sylvestris* L.	11 ÷ 100	1.4 ÷ 53.1	2.3 ÷ 32.0	19
Scandinavia	*P. sylvestris* L.	9 ÷ 212	1.9 ÷ 42.0	3.3 ÷ 32.4	117
The Ukraine and Byelorussia	*P. sylvestris* L.	24 ÷ 186	1.5 ÷ 54.6	1.6 ÷ 36.6	205
European Russia	*P. sylvestris* L.	10 ÷ 207	0.9 ÷ 54.0	2.2 ÷ 30.2	514
Turgay deflection	*P. sylvestris* L.	13 ÷ 110	0.3 ÷ 47.8	1.4 ÷ 27.4	411
Central Siberia	*P. sylvestris* L.	4 ÷ 430	0.5 ÷ 65.6	1.6 ÷ 28.8	587
China	*P. sylvestris* L. *P. massoniana* Lamb.	20 ÷ 100	8.0 ÷ 22.3	10.4 ÷ 19.0	9
Japan	*P. densiflora* S. et Z. *P. thunbergii* Parl.	22 ÷ 120	9.0 ÷ 60.9	9.5 ÷ 25.7	18
Total					1880
Trees in Plantations					
West and Central Europa	*P. sylvestris* L.	7 ÷ 50	0.5 ÷ 36.5	1.4 ÷ 21.0	77
Scandinavia	*P. sylvestris* L.	5 ÷ 143	1.2 ÷ 37.1	2.1 ÷ 25.6	196
The Ukraine and Byelorussia	*P. sylvestris* L.	8 ÷ 90	2.1 ÷ 42.9	2.2 ÷ 34.7	1010
European Russia	*P. sylvestris* L.	6 ÷ 78	1.5 ÷ 30.1	1.8 ÷ 32.6	160
Turgay deflection	*P. sylvestris* L.	9 ÷ 50	0.4 ÷ 21.7	1.4 ÷ 16.2	215
Central Siberia	*P. sylvestris* L.	10 ÷ 73	2.0 ÷ 36.0	2.4 ÷ 21.6	170
Iraq	*P. halepensis Mill.*	24	15.8	7.4	1
China	*P. tabuliformis Carr.*	17 ÷ 25	4.0 ÷ 12.0	3.3 ÷ 10.8	8
Japan	*P. densiflora* S. et Z. *P. thunbergii* Parl.	3 ÷ 53	1.7 ÷ 39.1	2.0 ÷ 18.7	130
Total					1967

Summer temperature is the greatest contributor that can explain the variations from 16% (Berner et al., 2013) to 50% (Bouriaud et al., 2005) of the total dispersion by estimating the stem biomass growth, using tree rings width. Moreover, the accurate relationship (positive or negative) of stand biomass depends on intra-annual temperature which was taken as a predictor. According to research by Khan et al. (2019), the relation of stand biomass is positive with the maximum intra-annual temperature and negative with the minimum or average annual temperature. With an inter-annual time step, the influence of summer temperature is more pronounced (Zubairov et al., 2018). But in long-term perspective, the prevailing influence is acquired by winter temperatures (Morley et al., 2017), as in the 20th century, winter temperatures in the Northern hemisphere are changing faster than summer temperatures (Emanuel et al., 1985; Folland et al., 2001; Laing and Binyamin, 2013; Felton et al., 2016). In terms of regression analysis, the comparison of weak temporal trend of summer temperatures and a steep trend of winter temperatures shows a smaller regression slope and a worse ratio of residual variance to the total variance by this regression. Taking the mean winter temperature as one of the independent variables, we get a more reliable dependence with a higher predictive ability.

The final structure of the model includes only those mass-forming indices that are statistically significant for all biomass components. It has the form as:

$$\ln P_i = a_{0i} + a_{1i}(\ln A) + a_{2i}(\ln D) + a_{3i}(\ln H) + a_{4i}(\ln D)(\ln H) + a_{5i}B + a_{6i}B\,[\ln(T+40)] + a_{7i}[\ln(T+40)] + a_{8i}(\ln PR) + a_{9i}[\ln(T+40)] \cdot (\ln PR) \qquad (1)$$

where P_i is biomass of i^{th} component in kg: A is tree

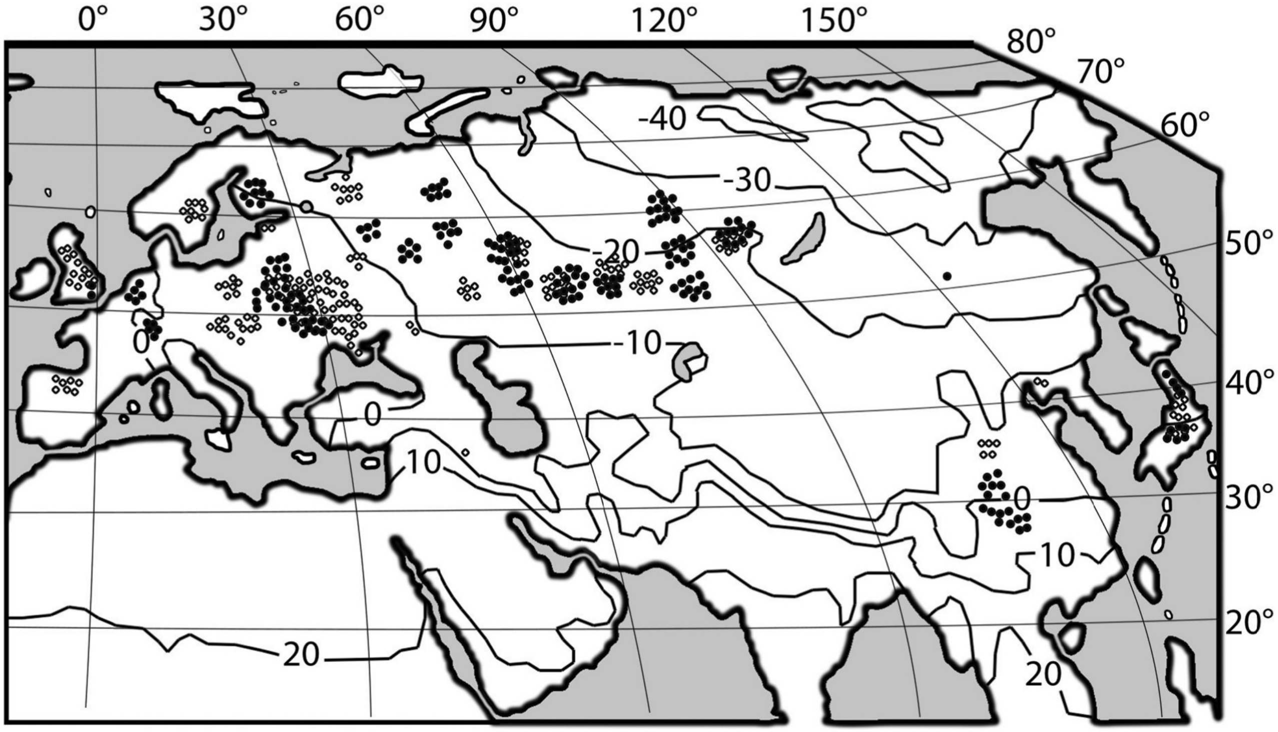

Figure 1: Distribution of sample plots, where 1883 and 1969 trees of natural (rings) and artificial (squares) origin correspondingly have been harvested, on the map of the mean January temperature, °C (World Weather Maps, 2007; https://store.mapsofworld.com/image/cache/data/map_2014/currents-and-temperature-jan-enlarge-900x700.jpg).

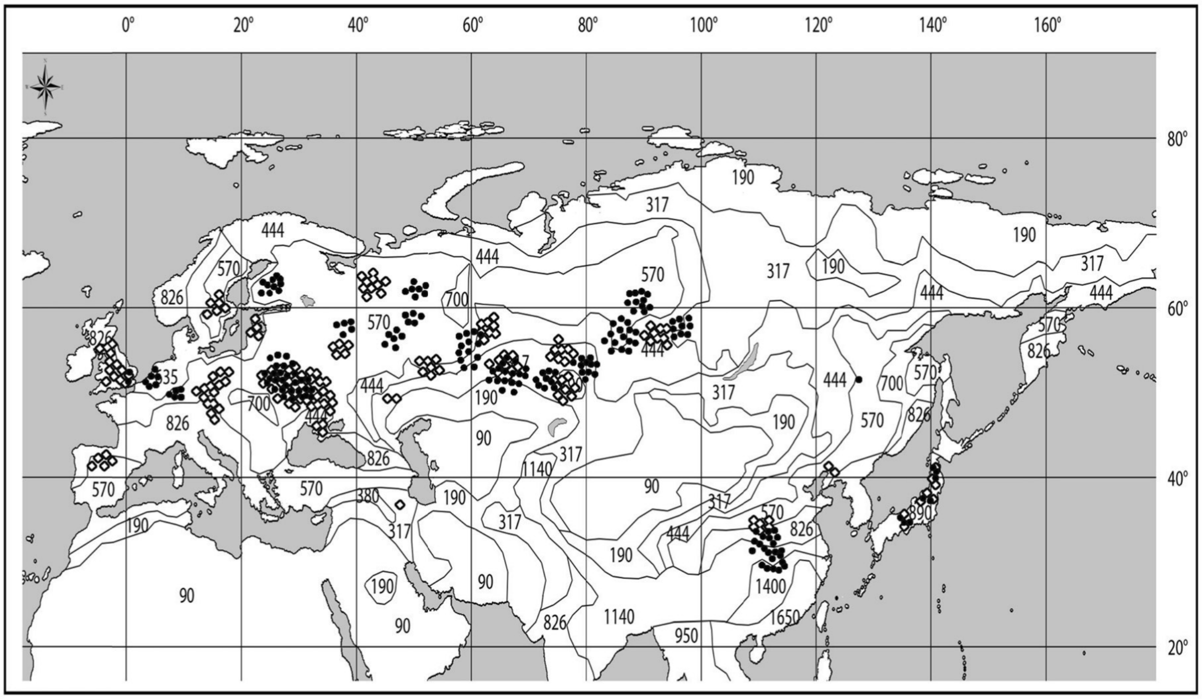

Figure 2: Distribution of sample plots, where 1883 and 1969 trees of natural (rings) and artificial (squares) origin correspondingly have been harvested, on the map of the mean annual precipitation, mm (World Weather Maps, 2007; http://www.mapmost.com/world-precipitation-map/free-world-precipitation-map/).

age in years; D is stem diameter at breast height in cm; H is tree height in m; i is the index of biomass component: stem over bark (P_s), needles (P_f), branches (P_b) and aboveground (P_a); B is the binary variable that coordinates the biomass values of natural pines ($B = 0$) and pine plantations ($B = 1$); T is mean January temperature in °C and PR is mean annual precipitation in mm.

Along with the three main mass forming variables - tree age A, diameter D and height H of a tree, the product of variables $(\ln D)(\ln H)$ is introduced as an additional predictor, the need for which was shown earlier by Usoltsev et al. (2019). Since the mean January temperature in the northern part of Eurasia has negative values, the corresponding independent variable is modified and subjected to log-log procedure as T+40.

When we introduce only one binary variable B in equation (1), the 3-D surface (temperature – precipitation – biomass) in X-Y-Z coordinates shifts between natural and artificial trees only along the Z axis by the value of the regression coefficient at the binary variable B. According to our assumption, the biomass of trees in natural stands and plantations reacts differently to changes in climate variables (Rodriguez-Vallejo and Navarro-Cerrillo, 2019). To include these differences in the designed model (1), along with B, we introduce the synergisms $B\cdot[\ln(T + 40)]$ and $B\cdot(\ln PR)$ as independent variables. To account for the simultaneous effects of temperature and precipitation, the synergism $[\ln(T + 40)]\cdot(\ln PR)$ is introduced in equation (1) as another independent variable.

Results

The regression coefficients of the multiple regression equation (1) were calculated using the Statgraphics software (see http://www.statgraphics.com/ for more information) as shown in Table 2. The calculations were done after the correction for logarithmic transformation by Baskerville (1972) and anti-log transforming procedure. The synergism $B(\ln PR)$ as an independent variable was not statistically significant. All regression coefficients of mass-forming variables in equations (1) are characterized by the significance level of 0.05 or better, and the resulting equations are reproducible.

Table 2: Characteristics of regression model (1) results

P_i	*Regression models*						
P_s	2.0143E-03	$A^{0.1525}$	$D^{1.5284}$	$H^{0.4322}$	$D^{0.1398(\ln H)}$	$e^{-0.1448B}$	$(T+40)^{0.0526B}$
P_f	7.842E-05	$A^{-0.4624}$	$D^{2.4422}$	$H^{-1.2824}$	$D^{0.1571(\ln H)}$	$e^{1.3265B}$	$(T+40)^{-0.3345B}$
P_b	6.524E-06	$A^{-0.1796}$	$D^{2.8848}$	$H^{-1.6954}$	$D^{0.1995(\ln H)}$	$e^{0.1512B}$	$(T+40)^{-0.0343B}$
P_a	2.218E-04	$A^{0.0407}$	$D^{1.7700}$	$H^{-0.1235}$	$D^{0.1778(\ln H)}$	$e^{0.2536B}$	$(T+40)^{-0.0629B}$

P_i	*Regression models*			*adjR*^{2}*	*SE**
P_s	$(T + 40)^{0.6901}$	$PR^{0.4292}$	$(T + 40)^{-0.1046(\ln PR)}$	0.987	1.24
P_f	$(T + 40)^{2.1870}$	$PR^{1.4287}$	$(T + 40)^{-0.3918(\ln PR)}$	0.900	1.61
P_b	$(T + 40)^{2.4966}$	$PR^{1.5638}$	$(T + 40)^{-0.4007(\ln PR)}$	0.926	1.66
P_a	$(T + 40)^{1.6918}$	$PR^{1.0370}$	$(T + 40)^{-0.2635(\ln PR)}$	0.986	1.24

* The abbreviation *adjR*^{2} is a coefficient of determination adjusted for the number of parameters;
SE – equation standard error.

The results of the equation (1) in tabular form represent a rather awkward table. We took the calculated data of component biomass from it for the age of 50 years, D equal to 14 cm and H equal to 13 m and built 3D-graphs of their dependence on temperature and precipitation (Figure 3).

Since many sample trees with an estimated belowground biomass are seven times less than the numbers of sample trees for estimation of aboveground biomass. It is considered that variability of belowground biomass estimation is higher, so we are at risk to get wrong patterns, which are logical contradictions (do not correspond) with the patterns shown in Figure 3. It is known that relative (dimensionless) indices are more integrated than absolute values (Detlaf and Detlaf, 1982), hence, they are characterised by genetically determined stability (Lyr et al., 1967). Therefore, the regression method is used to explain the variability of the ratio of belowground to aboveground biomass (*R/S* as root: shoot ratio), rather than the absolute values of belowground tree biomass. Initially, the structure of the

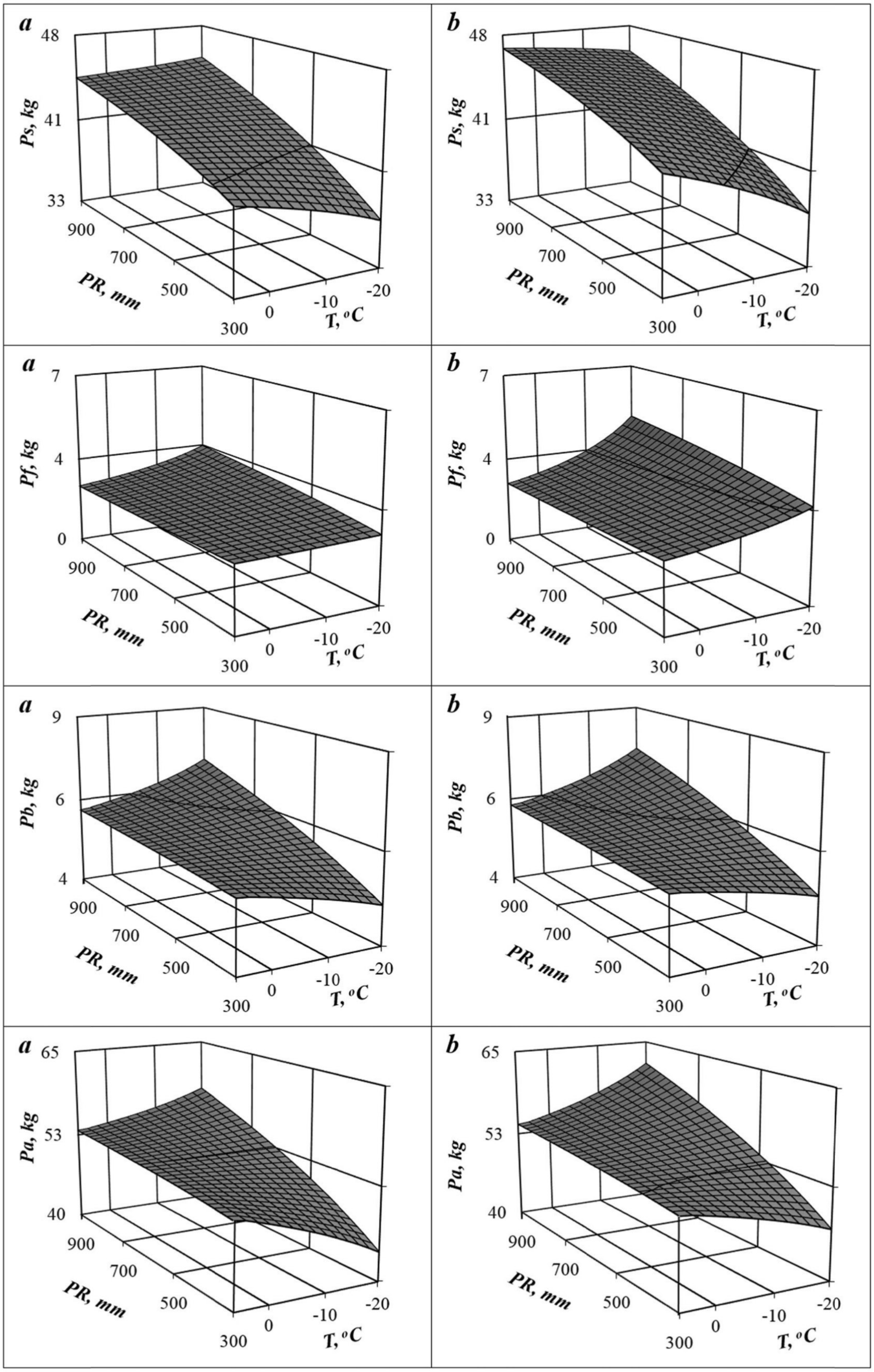

Figure 3: Dependence of pine tree biomass in natural stands (*a*) and plantations (*b*) based on mean January temperature (*T*) and mean annual precipitation (*PR*). Designations: *Ps, Pf, Pb* and *Pa* are, respectively, dry biomass in kg of the stem, foliage, branches and aboveground.

model (1) is adopted for the analysis of the *R/S* ratio. But, as expected, most of the parameters of the model (1) were not statistically significant, and the equation finally obtained is:

$$R/S = 1.562D^{-0.1949}(T + 40)^{-0.4666};\ R^2 = 0.153;\quad SE = 1.54 \tag{2}$$

The graphical interpretation is shown in Figure 4. Equation (2) is characterised by a fairly low coefficient of determination since it is known that the closer the relationship between two factors, lesser will be the relationship explained by known determining factors (Usoltsev, 1985). However, the Student's criteria determining the significance of the regression coefficients of the model (2) are quite high and are 6.9 and 5.9, which is more than 2.0. We can see that as we move from warm to cold climate, the absolute value of the *R/S* ratio for thin trees (DBH = 8 cm) increases from 0.17 to 0.26, and for thick trees (DBH = 32 cm) the increase is from 0.13 to 0.20, but in percentage terms, it does not depend on the tree size and increase in both cases by 48%.

Discussion

From the analyses of the 3D-surfaces as shown in Figure 3, we can distinguish two stages: first, we note the patterns common to trees in natural stands and plantations, and then, consider this in detail. It is established what and how the resulting patterns of natural trees are different from trees of plantations.

For the stem biomass, we see that it increases with increasing precipitation as well as with increasing temperatures in areas of insufficient moisture in all temperature zones. But as we move to areas of sufficient moisture, the last trend modifies.

The biomass of needles and branches increases in a cold climate with increasing precipitation. This tendency is also seen in areas of sufficient moisture with a decrease of the temperature. But as we move to areas of insufficient moisture and warm regions, these trends show changes.

Aboveground biomass sums up component-specific patterns by itself, amplifying the coincident ones and neutralising (compensating) those which are contradictory. In cold areas, there is a significant increase in biomass with increasing precipitation, but moving to the warm climate this trend disappears. In humid regions, the biomass increases with the decrease in temperature, but in water-deficient regions, the pattern changes to the opposite trend.

After analysing differences in the biomass trends of natural and plantation trees, it should be noted that, judging by the structure of the obtained equation (1), these differences are only related to changes in temperatures, not precipitation, since the synergism

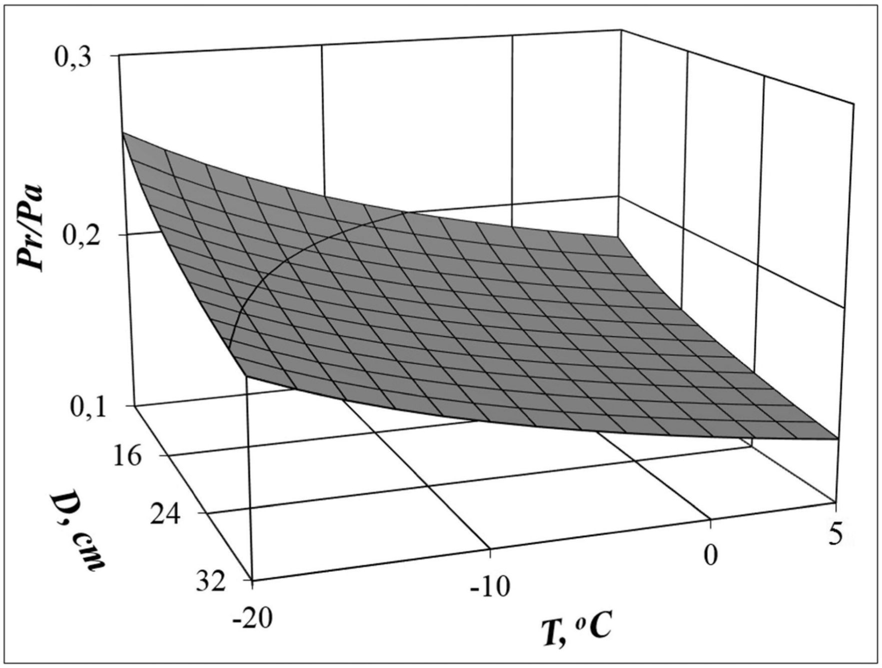

Figure 4: Change of the theoretical *R/S* ratio in relation to tree stem diameter under different mean January temperature (*T*).

B·(ln*PR*) was not statistically significant. The biomass of all components of plantation trees is higher than that of natural forest, but the percentage of this excess is different for different components and changes at different levels to changing temperature. Changes in the excess of biomass components of plantation trees over natural forests are shown in Table 3.

The table shows that as the move is from cold to warm climate, the increase in tree biomass of plantation over natural forest increases from 1.3 to 5.3% for stem biomass, decreases from 28 to 6% for foliage biomass, as well as from 4.8 to 2.1% and from 6.3 to 1.5% for branches and aboveground biomass, respectively, regardless of the precipitation level.

However, the most interesting question is how much the forest biomass will change with assumed deviations in temperature, for example, by 1°C and with a deviation in precipitation from the usual norm, for example, by 100 mm per year. The constructed model answers such question to single-trees. To do this, we consider the first derivative of our 3-dimensional surfaces (Figure 3), graphically, not analytically i.e., we take off the biomass difference interval (Δ, %%) corresponding to temperature interval at 1°C and precipitation interval 100 mm directly from the graphs or the corresponding tables, and get the answer in the form of three-dimensional surfaces, divided into plus and minus areas that correspond to the increase or decrease in the biomass of trees having the fixed age of 50 years, DBH of 14 cm and height of 13 m.

In this case, the differences between the biomass of natural forest and plantation trees become more obvious as shown in Figure 5. If the stem biomass of plantation trees increases as the temperature rises by 1°C over the entire precipitation range from 300 to 900 mm (the entire 3D surface is located above the zero planes), then the biomass of natural trees ranging from 300 to 700 mm (located above the zero planes), and in the range of 700 to 900 mm will be decreased (located below the zero planes).

The foliage biomass, in this case, decreases over the entire range of precipitation from 300 to 900 mm, both in natural forest and plantation trees (the entire surface is located below the zero plane), but the percentage of decrease in the plantation trees is greater than in the natural forest.

In terms of variations in the branch biomass, when the temperature assumes to increase by 1°C, natural and plantation trees do not differ significantly and an increase in the precipitation range from 300 to 500 mm and a decrease in the range from 500 to 900 mm can be observed.

When the temperature increases by 1°C, there is also a slight difference between natural and plantation trees in the aboveground biomass variations: the former increase in the precipitation range from 300 to 600 mm, and the latter increases in the range from 300 to 500 mm only.

When annual precipitation assumes to be increased by 100 mm at constant temperatures of January, then the aboveground biomass of stems, branches increases in all temperature zones, and the foliage biomass only increase in the range of temperature zones from –20°C to –2°C, for both natural forest and plantation trees as shown in Figure 6.

The similar modification of Figure 4 for the R/S ratio is shown in Figure 7. If the overall decrease in R/S ratio during the transition from cold to warm climate was 48%, then the decrease in R/S ratio "at the point", i.e., when shifting in the same manner by 1°C, was from –2.3% to –1.0%, regardless of the thickness of tree stems and their origin.

It is known that the solution to each new problem and the corresponding removal of the associated uncertainties generates several new issues. In our case, some uncertainties have arisen too:

1. The patterns of biomass amount change under assumed changes in climatic conditions as shown in

Table 3: Change in the excess percentage of different components biomass of plantation trees over natural trees due to variation in temperature of January

Biomass component	*Mean temperature of January, °C*						
	–20	*–16*	*–12*	*–8*	*–4*	*0*	*4*
Stems	1.3	2.2	3.0	3.7	4.3	4.8	5.3
Foliage	27.7	23.1	19.1	15.4	12.0	8.8	5.9
Branches	4.8	4.2	3.6	3.2	2.8	2.5	2.1
Above ground	6.3	5.2	4.3	3.5	2.8	2.1	1.5

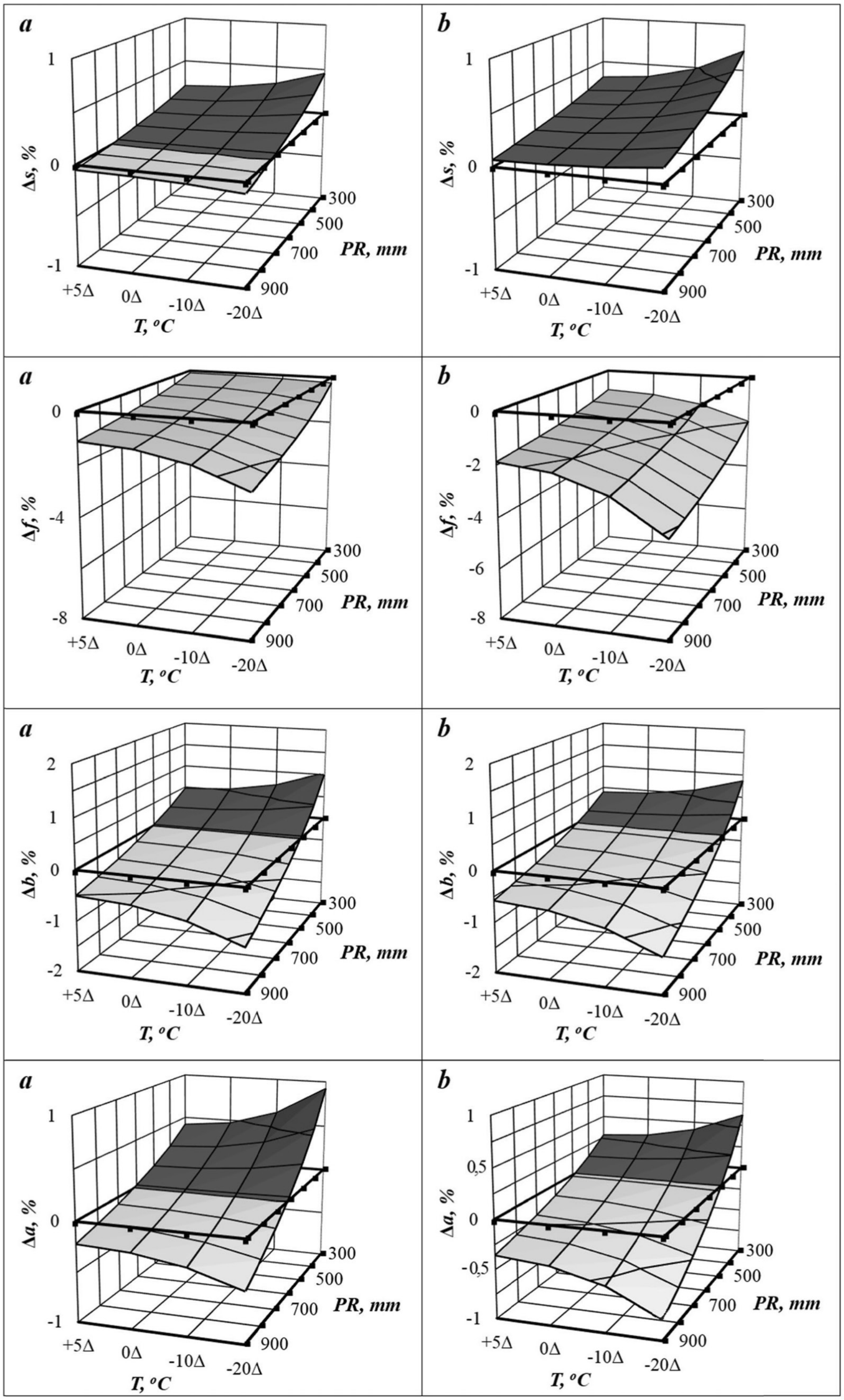

Figure 5: Change in tree biomass when temperature assumes to be increased by 1°C due to the expected climate change at temperature and precipitation. Symbols Δ*s*, Δ*f*, Δ*b* and Δ*a* on the coordinate axes means the change (± %) in biomass of stems, foliage, branches and aboveground, respectively, with the temperature increase by 1°C at the constant precipitation.

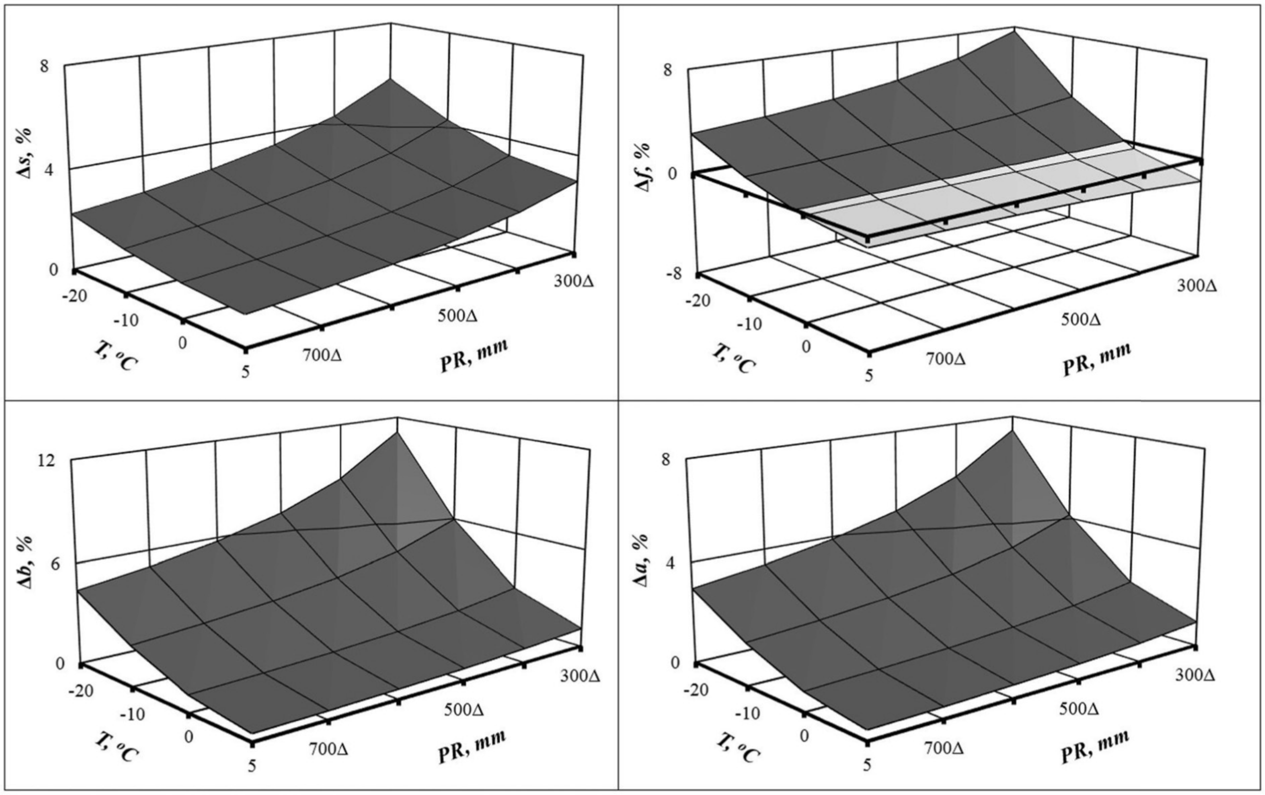

Figure 6: Change of tree biomass when precipitation assumes to be increased by 100 mm due to the expected climate change at different temperatures and precipitation. The symbols Δ*s*, Δ*f*, Δ*b* and Δ*a* along the coordinate axes represent the change (±%) in aboveground biomass of stems, foliage, branches, respectively, with precipitation increase by 100 mm and at the constant mean temperatures of January.

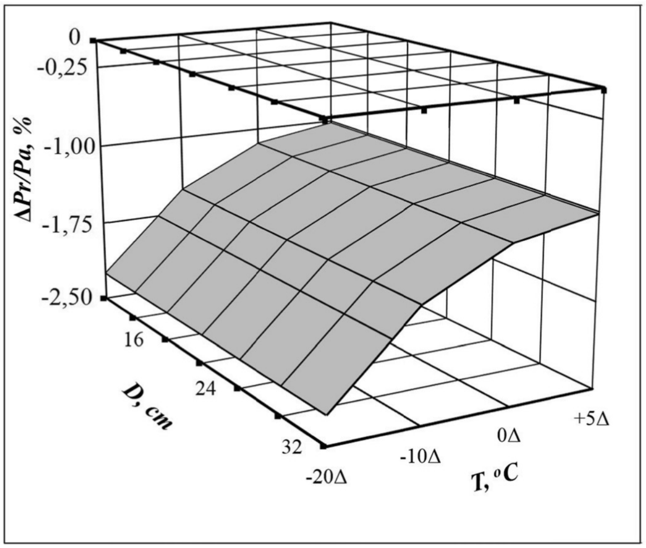

Figure 7: Change of R/S ratio when temperature assumes to be increased by 1°C due to the expected climate change at different temperatures.

Figures 5 and 6 are hypothetical. They reflect long-term adaptive responses of forest stands to regional climatic conditions and do not take into account the rapid trends of current environmental changes, which shows serious constraints on the ability of forests to adapt the new climatic conditions (Givnish, 2002; Alcamo et al., 2007; Berner et al., 2013; Schaphoff et al., 2016; Spathelf et al., 2018; Vasseur et al., 2018; DeLeo et al., 2019; Denney and Anderson, 2019). The law of limiting factors (Liebig, 1840; Shelford, 1913) works well in static conditions. With a rapid change in limiting factors (such as air temperature or precipitation), forest ecosystems in a transitional (non-stationary) state, in which some factors that were still not significant may come to the fore, and the result may be determined by other limiting factors (Odum, 1975).

2. A disadvantage of the database used in this study is the uneven spatial distribution and different representations of sampling sites for natural and

plantation trees over Eurasia as shown in Figures 1 and 2 and Table 1. In the regression analysis of biomass data we used the least-squares method, it estimates of biomass in ecoregions with a minimum number of sampling sites may be biased due to the greater "information weight" of ecoregions with the largest number of sampling sites. Methodological uncertainties causing biases in biomass amounts in parts of the individual tree may also affect the accuracy of the estimates.

3. The response of forests to climate change also depends on whether the photosynthetic benefits from increased atmospheric CO_2 compensates for increased physiological stresses from higher temperatures or not (Sperry, 2019). For example, moderate temperature rise (3°C) along with rising CO_2 concentration can increase net photosynthesis of plant population but can decrease biomass production because of increased respiration. However, an increase in temperature by 6°C can decrease both photosynthesis and biomass production, regardless of species' optimal temperature (Gustafson et al., 2017). There is a problem related to the associated effects with the simultaneous interaction of various factors (Pucko et al., 2011; Gray and Brady, 2016; Gustafson et al., 2017).
4. In equations (1), three mass-determining factors (*A, D*, and *H*) cover most of the explained variations: for the biomass of stem, needles, branches, and aboveground which are 94, 86, 91, and 87%, respectively. Climate variables and differences between natural forest and plantation trees account for only 6 to 13% of the variability. The structure of these "residual" variables is highly variable and heterogeneous. In addition, to the already noted uneven filling the initial data matrix, there are discrepancies between the age periods of mapping as shown in Figures 1 and 2, and calendar ages of different biomass components, between the large step of temperature and precipitation isolines on the maps and local topography features, as well as local soil differences, despite the fact that the soil zoning reflects the action of climatic factors (Dokuchaev, 1948; Rukhovich et al., 2019).

Taking into account the stated methodological and conceptual uncertainties, the results presented in this study provide a solution to the problem only in the first approximation and should be considered as preliminary ones and having not so much factual as methodological significance. They can be modified if the biomass database will be enhanced by additional data, mainly site-specific and strand-specific characteristics as well as by more advanced methodology.

Conclusions

The database compilation of natural forest and plantation of single-trees concludes that the above-ground and stem biomass of equal-sized and equal-aged natural forest and plantation trees increases with the rise of temperature in January and annual precipitation. This pattern is partially valid for the branches' biomass, and it has a specific character for the foliage one. The biomass components of plantation trees are higher than that of natural forest, but the percentage of excess biomass varies among different components and depends on the level of January's temperatures. However, it does not depend on the level of annual precipitation. As one moves from cold to warm climate, the excess biomass of plantation tree over natural forest increases from 1.3 to 5.3% in stem biomass, it decreases from 28 to 6% for foliage biomass, as well as from 4.8 to 2.1% and 6.3 to 1.5% for branches and aboveground biomass, respectively, regardless of the precipitation level. As one moves from warm to cold climate, the absolute value of the root: shoot (R/S) ratio for small trees (DBH = 8 cm) increases from 0.17 to 0.26, and for big trees (DBH = 32 cm) from 0.13 to 0.20. In terms of percentage, it does not depend on the stem size and increases by 48%. The results presented can be accounted for as the first approximation only.

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