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Scots pine (*Pinus sylvestris* L.) reaction to climate change in the provenance tests in the north of the Russian plain

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ABSTRACT

Species with continuous distribution area will be impacted by climate change in different ways. That is related to the population's geographical position and climate features of the population formation. Short-term response of Scots pine (*Pinus sylvestris* L.) was studied with taken into consideration intraspecies features of populations. Provenance tests in the Arkhangelsk (62.60 N, 39.98 E) and Vologda (62.60 N, 39.98E) regions located in the north of the Russian Plain were used. Provenances collection (23 provenances from the northern, middle, and southern taiga subzones and mixed forest zone) from areas with different climate characteristics was considered. Clinal variability and a reaction norm of vegetative and generative response to various levels of temperature change and seed transfer were studied. Average actual height and diameter values for 31-year provenances and calculated values for provenances were compared using 'latitudinal growth coefficient' proposed by I.V. Volosevich (1984) for the north of the Russian Plain. Provenance reproductive ability response was assessed using seed-bearing trees' numbers in provenances of the 1st class of age. Pine growing in the north of the Russian Plain would respond to warming by productivity increasing more significantly than pine growing in the south. Response of pine from the northern and middle taiga subzones on climate warming can be expected on 1.01 m and 1.12 cm to temperature rise by 100°C for height and diameter, and 0.85 m and 0.93 cm for seeds transfer to 1 degree of northern latitude to southward. Probable reaction norm for pine reproduction potential under temperature change by 100°C of the sum of the temperatures above 10ºC and seed transfer by 1 degree of northern latitude can be expected about 6%.

KEY WORDS

Pinus sylvestris L., provenances, climate change, height, diameter, reproduction

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INTRODUCTION

As present-day climatic changes have already become real (Zamolodchikov and Kraev 2016), for the forestry, it is important to take into account the impact of climate change to minimize their effect, to develop new methods of forest use and to employ their potential gains (Villeneuve et al. 2016; Kijowska-Oberc 2020; Keenan 2015). Both short-term and long-term impact of the future climate warming should be considered (Rehfeldt et al. 2002; Rehfeldt et al. 2003). Long-term impact upon forest ecosystems is related not only to temperature changes but also to temperature-associated humidity and insolation conditions, pathogen development and so on. According to scientists' predictions, long-term changes of forest ecosystems can be accompanied by redistribution of physiological and genetic characteristics of all species (Rehfeldt et al. 2003) and extend for several generations (Villeneuve et al. 2016; Beaulieu and Rainville 2005; Savolainen et al. 2004). Due to genetic changes, species will undergo the so called 'evolutionary adaptation' (Huang et al. 2013). Under sustainable warming, forest productivity can increase result from a longer growing period, higher growth rates, and higher photosynthetic activity (Rehfeldt et al. 2002; Beaulieu and Rainville 2005). However, productivity can also be decreased as a result from lower precipitations and drought development (Kapeller et al. 2012).

Short-term responses possible to study in experiences with provenances. Provenance tests used for progenies moved from the north towards south simulating climatic warming and, on the contrary, from the south towards north simulating climatic cooling. Provenance tests have been developed to solve problems of seed transfer. However, at present, they are used as the main test for simulation of short-term impact on growth rates of the main forest-forming species. This make possible to consider differentiated specific adaptation (Correia et al. 2010), so called thermal memory and phenotypic plasticity of species (Kijowska-Oberc et al. 2020; Velladares et al. 2014). Different phenotypic plasticity of species, including Scots pine, covering huge continuous area results in different growth response to climate changes (Shutyaev and Giertych 1997; Nakvasina et al. 2008; Reich and Oleksyn 2008; Matías and Jump 2014). Also, seasonal growth rates and phenological stages duration (Oleksyn et al. 1998; Pakharkova et al. 2014), chemical composition of needle and nutrients redistribution (Gray et al. 2019; Oleksyn et al. 2003) are change. Different responses of provenances and their localization within the area will cause different response arrangements used in the forestry (Mátyás 2006). Predicted results can be unreliable without regard to intraspecies response to climate changes (de Luis et al. 2013).

The objective of this study is to trace a trend of Scots pine (*Pinus sylvestris* L.) vegetative (diameter and height) and generative (cone production) components' response to transfer to the south and north plots using selection of provenances with different characteristics within test plots (Arkhangelsk and Vologda regions). We try to determine a norm of reaction of Scots pine to different temperature change levels.

MATERIAL AND METHODS

For simulation of Scots pine (*Pinus sylvestris* L.) response to climate changes, we selected some provenances growth in provenance tests established in the 1970s in the northern part of the Russian Plain at the Plesetsk Forestry in the Arkhangelsk region (62°60' N, 39°98' E) and Cherepovets Forestry in the Vologda region (59°02' N, 37°31' E). The Northern Research Institute for Forestry is a project supervisor. The test plots are located almost in the longitudinal direction that makes it possible to exclude meridian seed movement impact.

Scots pine provenances were selected according to the following requirements: 1) Warming and cooling simulation, that is, their habitats are located northward and southward of the test plot. 2) Provenances are located within or near the territory (63°30'–59°00' N, 36–58° E) studied by I.V. Volosevich (1984). That makes it possible to use 'latitudinal growth rates' proposed by Volosevich. 3) Quite equal survival of provenances in 31-year stands.

Studied provenances in the Arkhangelsk region test plot are represented by northern taiga and central taiga provenances. The differences in provenances locations were up to 6 deg. N, in temperature sum above 10ºC more than 560ºC. Provenances in the Vologda region test plot were form central taiga, southern taiga and the mixed forest zone. The differences in provenances locations were within 5 deg. N, temperature sum above 10ºC 400ºC. When provenance tests were established, the provenance set was intended for solving practical problems related to seeds transfer for reforestation and seed zonation. In every region, provenance set was limited from north and from south based on the data earlier obtained for author.

Average heights and diameters (DBH) of provenances obtained using a generally accepted method of provenances examination (Prokazin 1972). They are presented in inventory data in 2010 obtained by the Northern Research Institute of Forestry with participation of the author of the paper. For reproductive capacity assessment, data on seed-bearing of pine provenances of the 1st age class obtained by the author for test plot in the Arkhangelsk region and by N.V. Ulissova (1990) in the Vologda region were used. The maximum number of seed-bearing trees in 9 years of observation was taken into consideration. Geographical coordinates (northern latitude) and temperature sum above 10ºC were taken from the passport of the state registration of the provenance tests and corrected according to Agro-Ecological Atlas.

For pine reproductive characteristics assessment, local provenance of each test plot was used as reference provenance. Comparison of provenances growth was carried by actual height and diameter of pine in 31-year age provenance tests as well as by actual height values and estimated values for parent stands obtained with the use of latitudinal growth coefficients proposed by I.V. Volosevich (1984) for the latitude range of north of the Russian Plain. Results of the studies carried out by I.V. Volosevich are based on data obtained at 98 weather stations, analysis of growth rates presented by 13 Forestries, and data for natural studies of the Arkhangelsk Institute for Forestry and Wood Chemistry. The error in the calculations is no more than 3.5%. For each provenance, height and diameter were calculated using the reference provenance growth data and the latitudinal coefficient. Obtained estimated height and diameter values are compared with actual average height and diameter values for provenance in each test plot. This value shows difference (deviation) between the same age pine-tree growth rates in the parent stands and in the test plot. Geographical coordinates and temperature sum above 10ºC demonstrate the simulation of warming and cooling. Using this approach, heights and diameters of the same type and age of pine trees corresponding to mother population growing areas of the studied provenances were calculated. Difference between the estimated and actual heights and diameters in growing areas characterizes the response to moving (northern

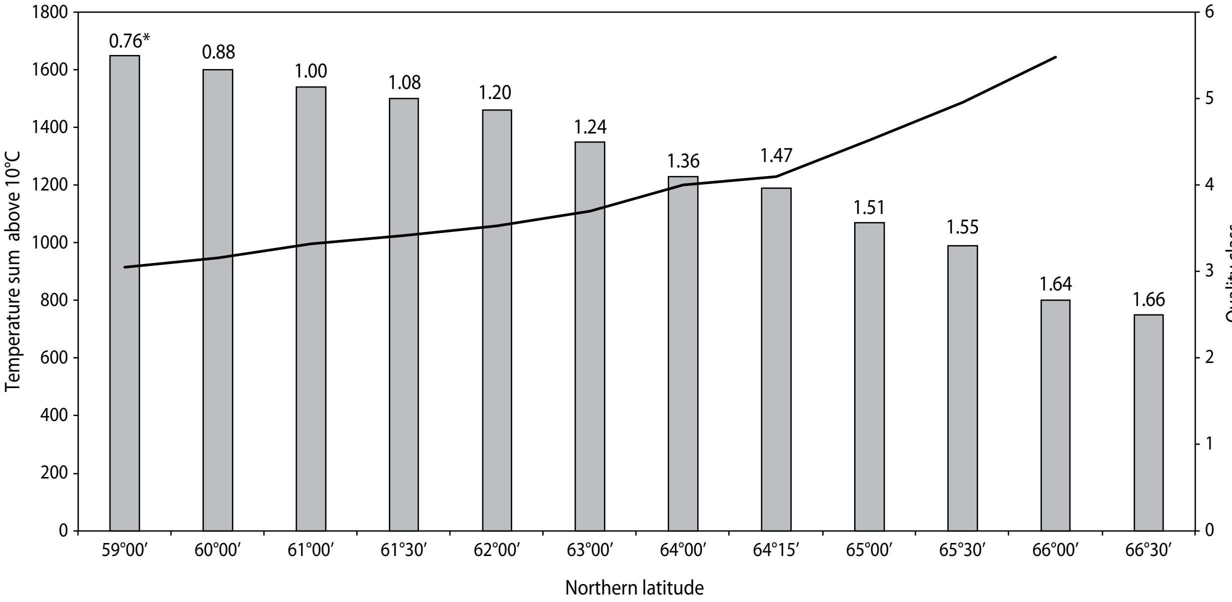

Figure 1. Sum of temperatures above 10ºC and the quality classes of Scots pine stands in the latitudinal gradient (according to Volosevich 1984). * – numbers indicate relative values (latitudinal growth coefficient), the columns – the sum of the temperatures above 10ºC, the line – the quality classes

latitude) and climate changes (cumulative temperature above 10ºC). Response in growing rates was compared with value deviation (northern latitude and cumulative temperature above 10ºC) for parent stands and for the test plot. Such an approach 'deviation value – response value' makes it possible to develop a norm of species response to climate changes and latitudinal moving.

The dependence obtained by I. V. Volosevich (1984) is shown in Figure 1. The proposed coefficients represent the relative sum of temperatures above 10ºC.

For the statistical data analysis, linear regression analysis was used and the Pearson correlation coefficient was calculated (SPSS v 22.0). Significant value was accepted at $P < 0.05$ level.

RESULTS

Set of studied provenances in the test plots in the Arkhangelsk and Vologda regions is different. However, it makes possible to trace Scots pine growth and reproductive ability response to simulated climate changes and trace the impact of environment in these test plots on growth and reproduction.

Table 1. Provenance locations and characteristics in the test plots in Arkhangelsk and Vologda regions

No[1]	Location	Forest vegetation subzone, zone[2]	Latitude (N)	Temperature sum above 10°C	Height [m]	Diameter DBH [cm]	Number of trees with female cone[3] [%]
			Arkhangelsk region				
1	Murmansk, Monchegorskii	NT[2)]	67°51'	991	7.1	9.1	60.1[4]
2	Murmansk, Kandalakshskii	NT	67°00'	966	11.0	10.9	55.3
3	Arkhangelsk, Pinezskii	NT	64°45'	1029	11.0	10.6	23.4
4	Arkhangelsk, Plesetskii	MT	62°54'	1230	11.1	12.0	16.1
9	Vologda, Totemskii	MT	60°00'	1463	11.1	11.6	0.0
12	Karelia, Chupinskii	NT	66°22'	1463	10.8	9.9	23.4
14	Karelia, Medvezhiegorsky	MT	62°54'	1233	12.2	12.8	16.1
15	Karelia, Pryazhinskii	MT	61°40'	1318	12. 1	12.2	0.0
16	Karelia, Sortavalskii	MT	61°50'	1530	11.7	11.2	0.0
17	Karelia, Pudozhskii	MT	61°40'	1436	12.3	12.9	0.0
			Vologda region				
4	Arkhangelsk, Plesetskii	MT	62°54'	1230	13.0	11.1	17.7[5]
8	Vologda, Cherepovetskii	ST	59°07'	1613	12.6	10.5	6.1
9	Vologda, Totemskii	MT	60°00'	1463	12.5	10.5	6.7
14	Karelia, Medvezhiegorskii	MT	62°54'	1233	12.6	11.3	33.6
16	Karelia, Sortavalskii	MT	61°50'	1530	13.7	11.2	25.8
17	Karelia, Pudozhskii	MT	61°40'	1436	13.1	10.5	31.4
19	Leningrad, Lisinskii	ST	60°00'	1689	14.8	13.2	4.8
22	Pskov, Pskovskii	MF	57°50'	1760	13.0	10.8	0.0
23	Novgorod, Krestetskii	MF	58°15'	1754	12.0	10.5	0.0
24	Estonia, Alsaceskii	MF	58°10'	1767	12.0	10.0	0.0
42	Tver, Bezhetskii	ST	57°45'	1813	14.0	12.0	7.0
47	Kostroma, Manturovskii	ST	58°30'	1739	14.2	12.5	1.9
48	Kostroma, Kostromskoi	ST	57°50'	1828	13.2	11.3	3.8

[1] provenance numbers according to State Registry; [2] by S.F. Kurnaev (1973): NT – northern taiga. MT – middle taiga. ST – southern taiga. MF – mixed forest; [3] The maximum number of seed-bearing trees in the period of 9 years; [4] by E.N. Nakvasina, T.V. Bedritskaya. (1999); [5] by N.V. Ulyssova (1990).

Since some trees increase growth, and others reduce it, the average heights of pines become close to each other (Tab. 1) (Nakvasina et al. 2008). Height and diameter levelling out in the collection is related to different progenies' responses to warming and cooling (transfer to the test plot for growing in other environment) and depends on the optimal conditions for growing. It is clearly shown in Figure 2. For pine provenance collections selected for study variability coefficient is low, 11.9 and 10.9% in the Arkhangelsk region, 5.6 and 7.8% in the Vologda region, respectively for height and diameter.

Provenances from the northern and central taiga subzones growing in the Arkhangelsk region show close correlation between height and diameter and their geographical position of and temperature sum above 10ºC in the parent stands (Tab. 2). These provenances increment growth rate by moving southward and maintain inherited growth rate typical to their natural populations. The provenances from northern and cen-

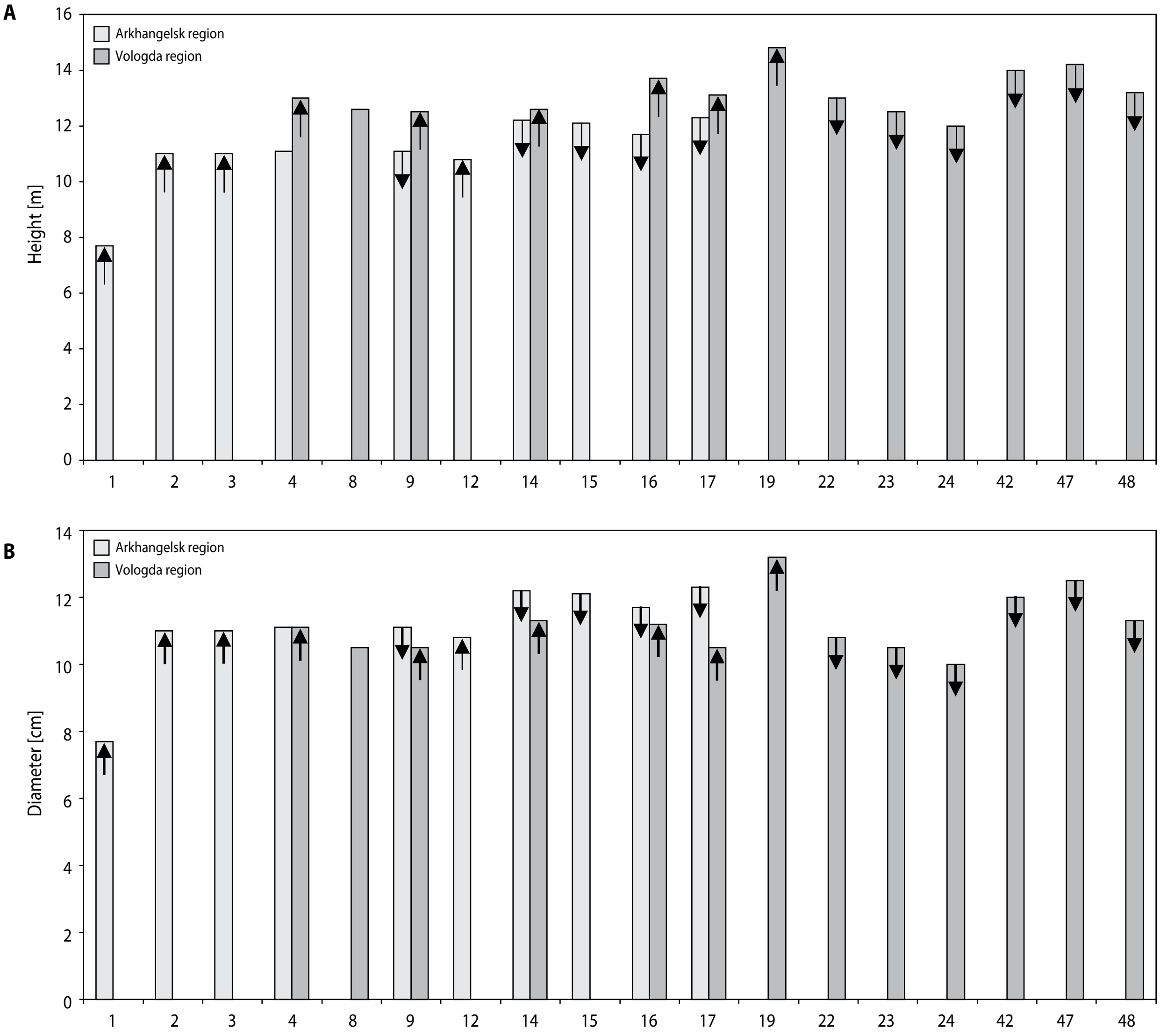

Figure 2. Growth of Scots pine provenances in 31-year-old provenance tests in the Arkhangelsk and Vologda regions: the up arrow shows the progenies transfer direction from the original stands to the test plots from north to south (imitation of warming). The down arrow indicates transfer from the south to the north (imitation of cooling); provenance numbers according to Table 1

tral taiga subzones in better climate conditions (warming simulation) grow more intensive but do not reach the size of pine belonging to the local (standard) provenance (No 4) that is not impacted by moving effect and is adapted to habitat conditions.

Table 2. Correlation between the height and diameter of pine provenances and northern latitude and the sum of temperatures above 10°C in the places of growth of the original stands

Parameters	Arkhangelsk region		Vologda region	
	height [m]	diameter [cm]	height [m]	diameter [cm]
Latitude (N)	–0.694*	–0.773***	–0.031	–0.013
Temperatures sum above 10°C	0.578	0.632*	0.238	0.168

*** significant at 0.1% level, * significant at 5% level.

In contrast to the use of actual provenance growth data in test plots (Tab. 2), the correlations by deviations are higher (0.6–0.9) compared to the absolute values of the height and diameter of the pine (0.2–0.7) and allow to make more accurate forecasts (Tab. 3, Fig. 3, Fig. 4).

Table 3. Correlation between deviations of the actual and estimated height and diameter of pine provenances and deviations of northern latitude and the sum of temperatures above 10°C of original stands from test plots

Parameters	Arkhangelsk region		Vologda region	
	height deviation[2] [m]	diameter deviation [cm]	height deviation [m]	diameter deviation [cm]
Latitude (N) deviation[1]	–0.918***	–0.952***	–0.759**	–0.644*
Temperature sum above 10°C deviation[1]	0.858***	0.895***	0.598	0.506

[1] deviations of parameters (northern latitude and temperature sum above 10°C) in the original stands from the test plots; [2] deviations of the actual height and diameter in test plots from calculated values in the original stands. *** significant at 0.1% level, ** significant at 1% level, * significant at 5% level.

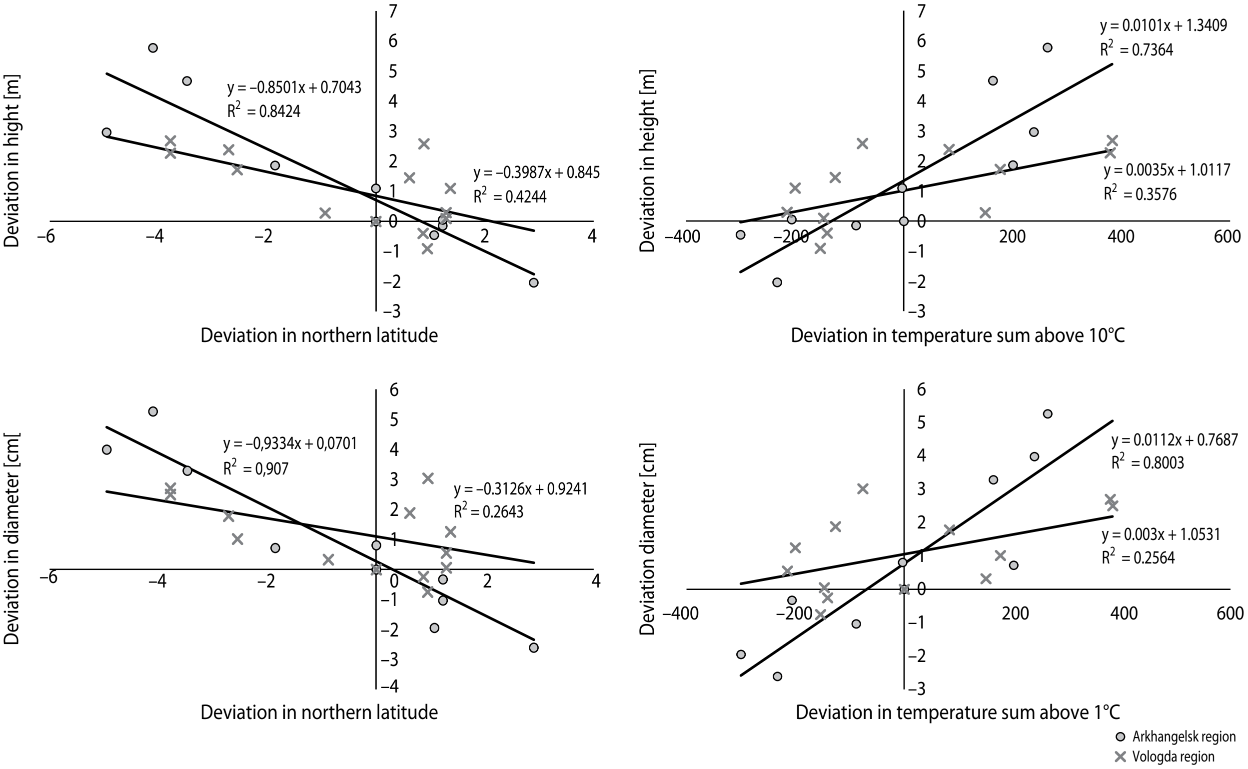

Figure 3. Dependence of Scots pine height and diameter deviation from deviation in northern latitude and temperature sum above 10°C in test plots in Arkhangelsk and Vologda regions

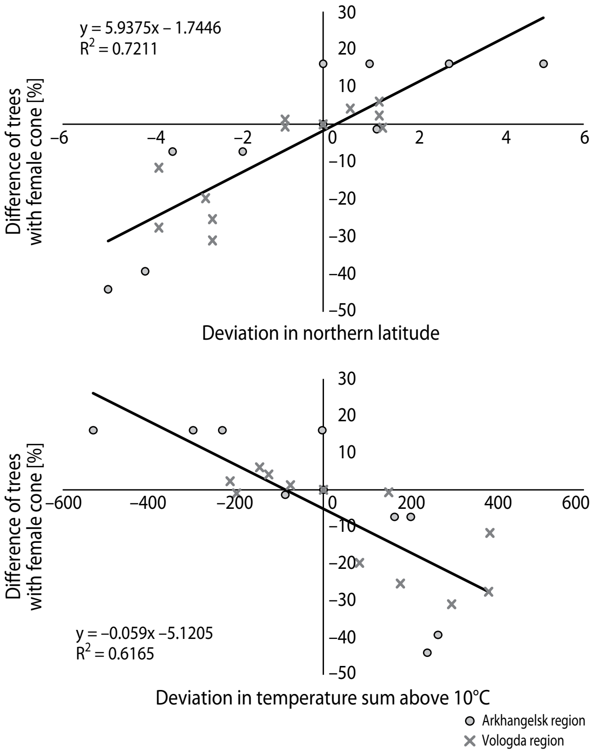

Figure 4. Relationship between deviation in the number of trees with female cone with deviations of the northern latitude and the sum of temperatures above 10°C in the provenance tests in Arkhangelsk and Vologda regions

DISCUSSIONS

In provenance test in the Vologda region characterized by better climate condition, provenances from the central, southern taiga subzones and mixed forest zone react less to climate changes (difference in parent stands and test plot). However, maintaining the inherited growth rate, southern provenances from the southern taiga subzone and mixed forest zone mostly exceed pine population of local provenance (No. 8) in height and diameter. Earlier we pointed that northern provenances of Scots pine growth slowly in provenance test in the north of the European part of Russia (Nakvasina et al. 2008).

Similar but less response of pine provenances in better environmental conditions was noted by B. Persson (1998). Correlation is extremely low due to pine growth levelling under conditions in the Vologda region (Tab. 2). The decrease in the response of trees to transfer is typical in the more southern test plots (Leites et al. 2012), but at the same time, one should not exclude specific features of species population. Thus, in provenance test in the Vologda region, the provenance from the Leningrad region (No 19) is prominent because of its better growth rates (Tab. 1, Fig. 2).

Assessment of response of Scots pine provenances to climate changes based on actual heights is mistaken. It is required to compare species growth rates in the test plots and in the parent stands. However, it is impossible to select the same age progenies in the mother population sites, as well as to select artificial stands grown with the use of similar technologies. The approach proposed by I.V. Volosevich (1984) makes it possible to avoid difficult searches for in-situ objects.

Regional climatic changes at high latitudes were studied and confirmed by L. Hellmann et al. (2016) for the territory of Eurasia. Other authors (Briffa et al. 2002; Nissinen et al. 2020; Hughes et al. 2019) showed the role of the temperature factor on the growth of tree species, including pine, both under natural and controlled conditions. According to G. King et al. (2013), plant growth is more dependent on climatic characteristics than on genetic characteristics.

However, the relationship between growth and the temperature conditions of a particular month did not always give the expected results (Hellmann et al. 2016). Using the temperature sum above 10ºC, proposed by I.V. Volosevich (1984) may be useful.

Differences in climatic characteristics in the areas of growth of the initial stands and test plots are traditionally taken into account in experiments with provenances (Person 1998; Renfeldt et al. 2003; Taeger et al. 2013). The assessment is carried out for a number of factors, including temperature conditions. Experiments show the response of tree species to growth when transferred to warm environment.

For provenances of the northern and middle taiga subzones in the test plot in the Arkhangelsk region distinct regularity of progenies response increase in height and diameter to climate changes is traced. The more difference in distance in latitudinal direction and in cumulative temperature above 10°C between parent stands and test plots cause stronger pine response.

Pine provenances in the Vologda region test plot demonstrate weaker response but correlation coefficient is significantly higher than for actual data use. In this case, weaker response results from the fact that moving within 1.5–2 degrees N to northward and change of cumulative temperature above 10°C by 100–200°C into the favourable conditions in the southern taiga subzone does not reduce growth. This is rather support growth specific features of pine population if its growing areas are close to the test plot by geographical and climate characteristics.

Graphical interpretation of relation of deviation in northern latitude and cumulative temperature above 10°C with Scots pine response in height and diameter is shown in Figure 3. High values R^2 (0.80–0.91) for test plot in Arkhangelsk region make it possible to estimate a reaction norm in height and diameter for Scots pine as a response to climate change. Short-term response of pine from the northern and middle taiga subzones in the north of Russian Plain on climate warming can be expected on 1.01 m and 1.12 cm to temperature rise by 100°C for height and diameter, and 0.85 m and 0.93 cm for seeds transfer to 1 degree of northern latitude to southward.

These values are similar to the data shown earlier (Prescher and Stihl 1986) for the southern and central Sweden. Scots pine moving 2 degrees northern latitude southward resulted in 1.25–2.00 m height increment in 30-year old stands. At that, the tree trunk's quality was higher.

Study of reproductive characteristics of 1-class age pine provenances (Nakvasina and Bedritskaya 1999; Ulissova 1990) indicated climate change impact on generative features. Phenotypic response of the Scots pine to temperature rise was evident both in growth and reproductivity. The progenies have changed in reproductive age, number of reproductive trees, number of male and female cone, seeds quality (Nakvasina and Bedritskaya 1999). It allowed us to start predictive studies of pine growth and reproductivity under the climate changes (Nakvasina 2003, 2014; Nakvasina et al. 2018). Northern provenances in warmer conditions start reproductivity more active. In some cases, maximum possible number of seed-bearing trees was attained. Warming simulation (seeds of the northern pine population transfer to southward) resulted in not only seed-bearing trees and female cone number increase but also accelerated maturity of northern progenies. At the same time, provenances from the southern taiga subzone and mixed forest zone started reproduction from male cone formation and female cone production started some years later.

Assessment of Scots pine response to warming and cooling simulation by seed-bearing trees number (Tab. 1) was performed for the same provenances in Arkhangelsk and Vologda regions test plots. In provenances of the 1st-class age, the share of seed-bearing trees (maximum value for 9 years of reproduction) depends on the northern latitude and cumulative temperature above 10ºC in parent stands location. Correlation coefficient is 0.851 and -0.788 respectively for provenances growing in the Arkhangelsk region test plot and 0.814 and -0.768 respectively for provenances growing in the Vologda region test plot. Irrespective of growing conditions (middle taiga and southern taiga subzones), distinct regularity of Scots pine response in reproductive ability is traced. This is related to the distance and change temperature factor in the test plot compared to the parent stands (Fig. 4).

Number of seed-bearing trees (trees forming female cone) is increased as a result of climate warming or seeds southward transfer. It stimulates reproductive activity of progenies with quite distinct clinal variability (R^2 = 0.72–0.62) related to warming and cooling simulation. As well as on correlation by growth rates, weaker response of pine from southern provenances and less of progenies reproductive activity in favourable conditions in the Vologda region is shown. For populations at the pine area edge, including northern provenances (the north of Russian Plain), increase in response to climate changes can be related to species adaptation incompletion resulting in wider range of biological forms (Kozubov and Bobkova 1990).

On cooling simulation (seeds transfer towards to north), female reproductive activity decreases, at the same time protandrous female cone formation is enhanced. With certain assumption, a probable reaction norm for Scots pine reproduction potential (deviation by number of seed-bearing trees) under temperature change by 100°C and seed transfer by 1 degree of northern latitude can be expected about 6%.

Earlier, our studies (Nakvasina and Bedritskaya 1999; Nakvasina 2014) showed that northern pine ecotypes growing in southward areas (warming simulation) produce more seeds amount, seeds mass and germination capacity increase, and empty seeds amount decreases. In some years, seeds mass (1000 seeds) for northern taiga pine was 6 g and more, and germination was about 90%, corresponding to the same indices for pine from middle and southern taiga. Under increasing of temperature sum above 5°C at least of 300–700°C mass of pine seeds increased. At the same time, on cooling simulation even within 200°C, pine seeds amount reduced. All that proves necessity in detail consideration of problems related to specific features of Scots pine response to climate changes.

Conclusions

In this regard, it is essential to find responses in species growth in provenances original places and in the test plots with taken into account different climate conditions (Rieksts-Riekstins et al. 2014; Gömöry et al. 2012). This allows us to define the so called reaction norm (Mátyás1989; Prescher and Stihl 1986). It is rate variation value in a certain range of climate changes determined in a phenotype in accordance with species (its provenance) adaptation to environment.

Experiments with Scots pine and other species in various countries indicated that provenances from sites located to the north of a test plots have higher growth response to warming than those located southward (De la Mata et al. 2013; Matías and Jump 2014; Rehfeldt et al. 2003). However, at the same time, the northern progenies do not grow up to parameters of the southern provenances (Nakvasina et al. 2008; Prudhomme et al. 2018). Reasons for this phenomenon can be related to genetic control, specific growth adaptation to climatic conditions of a geographical race formed as a result of pine dissemination during the Holocene in the north of the Russian Plain. The northern Scots pine races have lower inherited requirement in cumulative temperature for growth (Oleksyn et al. 1998; Leites et al. 2012). Southern provenances can reduce productivity due to decrease of precipitation and higher aridity of growth conditions (Huang et al. 2013).

Climate changes within the Russian territory will take place gradually, and in different geographical regions, their level will differ. Scots pine with its continuous distribution area in Eurasia will show diverse short-term response. This reaction is impacted by population geographical position and climate conditions of its formation in stable climate period after pine distribution in Holocene. At the same time, inherited growth and development characteristics will respond to climate parameter change. This response is a result due to the geographical position of pine and its population peculiarities as a result of phenotypic plasticity.

Pine-trees growing in the north of the Russian Plain (northern and middle forest subzones) will increase their reproductive ability in response to climate changes, first of all related to temperature increase, more active than pine-trees growing in the southern taiga subzone and mixed forest zone. In favourable growing conditions (southern taiga subzone, mixed forest zone), pine response is more related to specific features of populations.

Pine reproductive ability response will be also different, at least in young forests, first of all, in number of seed-bearing trees. It can result in seed stock, undergrowth density increase in forest and so on. However, at present, the problem of pine and other forest-forming species reproductive ability response is still under consideration. Reproduction processes (seed-bearing intensity, seed stock increase, etc.) can be changed by temperature factor associated with the climate change. Seasonal weather change, drought period prolongation can influence the pollen quality and pollen conditions, germ and endosperm development disturbance. However, just now one can see that short-term response of pine reproductive ability is expected and it should be taken into consideration when predicting climate change as well as growth response. Differentiated response of Scots pine should be considered in forest management development adapting to climate change.

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