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COMPETITIVE STRENGTH EFFECT IN THE CLIMATE RESPONSE OF SCOTS PINE RADIAL GROWTH IN SOUTH-CENTRAL SIBERIA FOREST-STEPPE

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ABSTRACT

This paper presents a method for classification of trees in groups depending on parameters of the age trend in tree-ring width. The method is tested on a sample containing 194 trees of Scots pine (*Pinus sylvestris* L.) growing in the forest-steppe zone of the South of Central Siberia. The climatic response of tree-ring width in such climatic conditions is complex. The influence of temperature in May-September is negative (moisture reducing). Warm-season precipitation serving as a source of moisture is a positive factor. Another positive factor is cold-season precipitation as frost protection. We determined the dependence of this response on the local conditions (soil, landscape and anthropogenic factors). The competitive strength of the trees influences both the sensitivity of individual trees to extreme climatic factors and the timing of growth processes. The latter implies the duration of the period of significant response to climate. It appears promising to take this influence into account in dendroclimatic reconstructions by using separate clusters of trees based on the competitive strength and having the maximum response to the reconstructed factor.

Keywords: tree-ring width, climate response, forest-steppe zone, Scots pine, competitive strength, age trend, cluster analysis.

INTRODUCTION

The quality of climate reconstructions using long tree-ring chronologies is central in dendroclimatology. Several studies (*e.g.* Nicault *et al.* 2010; Babushkina *et al.* 2011; Schuster and Oberhuber 2013) have been dedicated to the problem of identifying and quantifying the influence of various non-climatic factors affecting tree-growth. Important non-climatic factors are tree age, position in the stand (competitiveness), and local soil (substrate) conditions. It should be noted, that the sensitivity of a tree to climatic influence depends on its size. There are data from the Alps showing that the response of spruce growth rate to rainfall in May to June depends on the trunk diameter and height of the tree, which determine the competitiveness of the tree (Schuster and Oberhuber 2013). Studies of the differences in climatic response of the trees, separated into groups based on the diameter of the trunk (Campelo *at al.* 2013) and the class of the crown (Martín-Benito *et al.* 2008), also showed the dependence of the level of tree adaptation to extreme precipitation and temperatures on these parameters of tree size.

The competitive strength of a tree is determined by the rate of change of tree size with age. Mathematically it can be expressed through the parameters of the function of the age trend. The competitive strength depends on many factors including the conditions of the growth location

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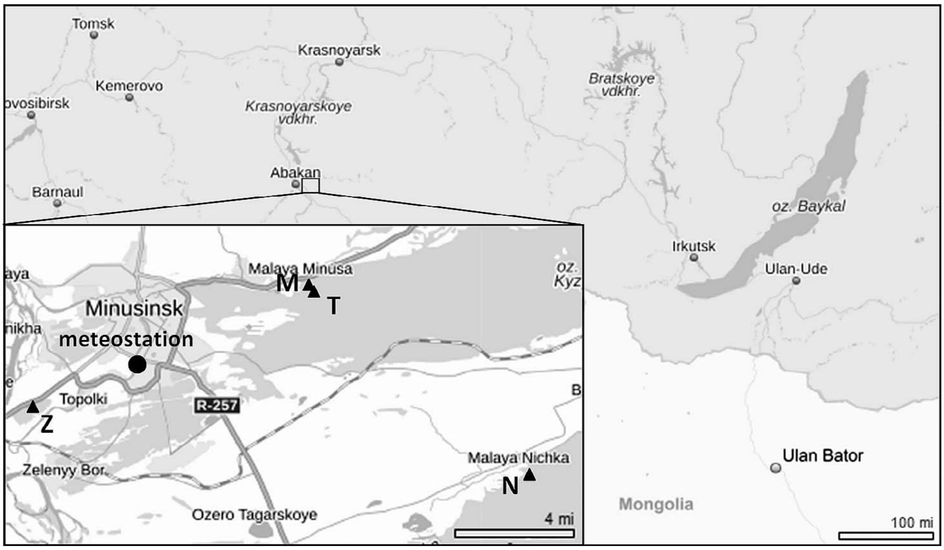


Figure 1. Location of the study area with insert showing sample collection sites (▲) and meteorological station "Minusinsk" (●).

and competitive interactions between trees. Other studies have used the terms "growth rate" (Nicault *et al.* 2010) or "growth energy" (Lebedenko 1969). However, few studies have specifically investigated the direct influence of the competitive strength on the climate response of trees. Rather the goal has been to improve methods of standardization of chronologies used in dendroclimatological reconstructions. For example, in using regional curve standardization, Esper *et al.* (2002) separated the individual age curves into two groups based on their "linearity" and "non-linearity", whereas Melvin (2004) and Briffa and Melvin (2011) made a distinction between "fast growing" and "slow growing".

In this paper we selected Scots pine from the forest-steppe zone of the Altai-Sayan region to analyze the influence of the competitive strength on the climatic response. This region is interesting because of its complex nature and pronounced influence of the local conditions at the growth site (Magda and Zelenova 2002; Magda and Vaganov 2006; Babushkina *et al.* 2011).

Using a large sample set, we consider (1) regional climatic response of radial growth of Scots pine and its dependence on local conditions, (2) differences in the climatic response of groups of trees that are classified based on competitive strength, and (3) the suitability of trees for dendroclimatological reconstructions depending on their competitive strength in the forest-steppe zone of Southern Siberia.

METHODS

The study was conducted in the Minusinsk belt conifer forests along the two tributaries of the Yenisei River in the steppe natural zone in southern Central Siberia (Figure 1). These forests consist mainly of Scots pine (*Pinus sylvestris* L.) with an admixture of deciduous trees (see Table 1). Scots pine is a stable component of forest-steppe zones and near-taiga forests, because it is less demanding on moisture and the soil in comparison with other conifers in the region. It is widespread in Central Asia and plays an important role in the regional economy. Thus it is of interest for use in dendroclimatological research.

The climate of the study area is continental, moderately cold (Grigoryev and Budyko 1960). According to the meteorological station "Minusinsk" (#29866, 53°41′N, 91°40′E, 250 m a.s.l.), the average annual temperature here is about 1°C (Figure 2). The beginning of the vegetation period (when average daily temperatures rise above 5°C) occurs at the end of April. The period of the year with temperatures above 10°C is 110–120 days. The average annual precipitation is 330 mm. The

Table 1. Brief characteristics of the sample collection sites.

Site	Stand	Understory	Soil and Topography
Z	Pure stand of *Pinus sylvestris*, density is medium.	Shrub layer (30% density) – *Cotoneaster melanocarpus*, *Caragana arborescens*, *Spiraea chamaedrifolia* et al. Herb layer – forbs with graminoids.	Soil is sandy with 10–15 cm of humus layer (7–10% humus). Soil moisture is medium. Relief is quite flat, slopes up to 5.
M	*Pinus sylvestris* is associated with *Betula pendula.*	Shrub layer – same with Z. Herb layer – graminoids with forbs. Moss layer density is 10–15%.	Soil is sandy with 8–10 cm of humus layer (7–10% humus), less dense than on Z. Soil moisture is medium. Relief is quite flat, slopes up to 10.
T		Shrub and herb layers – same with M. Moss layer density is 5–10%.	Soil is same with M but more sandy. Soil moisture is low. Relief is quite flat, slope of hill 15–45.
N	*Pinus sylvestris* is associated with *Betula pendula* and *Populus tremula*.	Shrub layer (35% density) – *Caragana arborescens, Cotoneaster melanocarpus, Rosa acicularis*. Herb layer – graminoids (mostly *Carex macroura*) with forbs.	Soil is a little sandy, contains more humus (10–15%). Soil moisture is from medium to wet. Relief is rolling plain, slopes up to 10. There are many little streams and swamp sites.

dynamics of precipitation is characterized by a pronounced summer maximum, with 81–91% of the precipitation falling in the period April through October. The precipitation maximum is in July (67 ± 30 mm) and minimum is in February (7 ± 5 mm).

The first half of the growing season is characterized by a deficit of atmospheric moisture, as indicated by the low values of the Selyaninov's hydrothermic coefficient. This coefficient is defined as the ratio of total precipitation to the sum of temperatures divided by 10 (Selyaninov 1937). The values of the coefficient at the study site are 0.94 ± 0.53 in May and 1.06 ± 0.51 in June. Amount of precipitation in the second half of the season is more optimal (Selyaninov's hydrothermic coefficient of 1.24 ± 0.71 for July and 1.18 ± 0.55 for August). We used monthly data from the meteorological station for the mean temperature and amount of precipitation for the years 1915–2012 (Figure 2). In the study area, significant negative correlations between precipitation and temperature from May to September are observed ($R < -0.22$, $p < 0.05$), the strongest in July ($R = -0.413$, $p = 0.00003$). From October to April temperature and precipitation are not correlated.

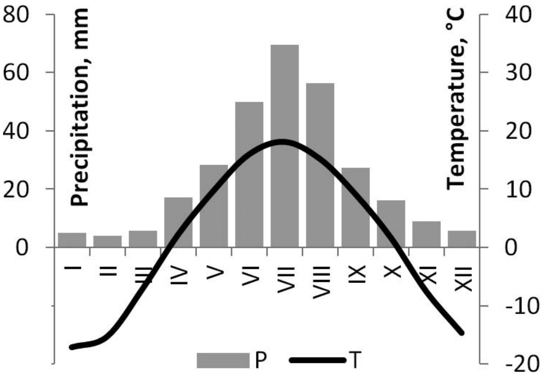


Figure 2. Averaged monthly data of temperature and precipitation for years 1915–2012 from the meteorological station "Minusinsk".

The samples (cores of living pine trees taken on the height of 1.3 m) were taken at four sites at a distance of up to 25 km from the meteorological station "Minusinsk" (Figure 1b): "Malaya Minusa" (M, 310 m a.s.l.) – 36 trees, "Taraska" (T, 360 m a.s.l.) – 34 trees, "Malaya Nichka" (N, 370 m a.s.l.) – 29 trees, and "Zeleniy Shum" (Z, 310 m a.s.l.) – 95

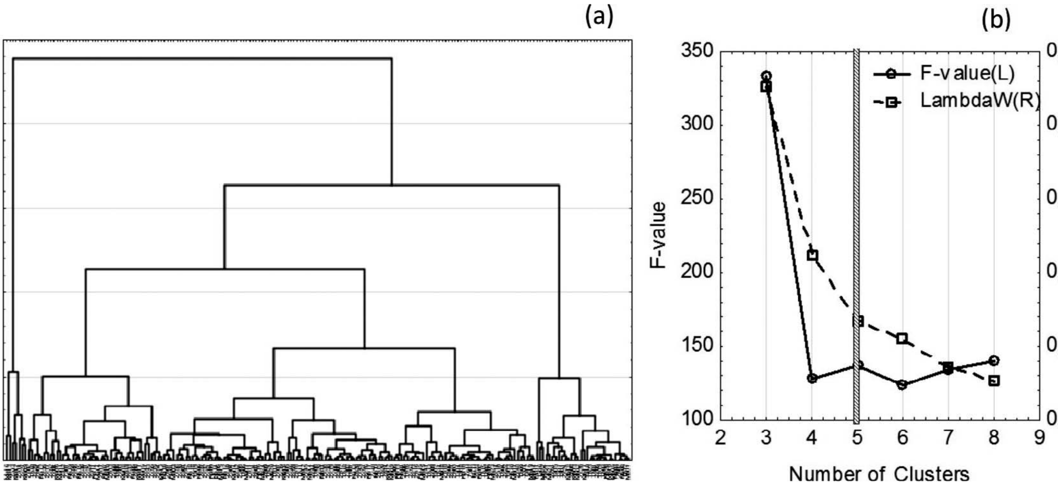


Figure 3. Classification of the chronologies by the parameters of age curves: (a) a hierarchical classification; (b) quality indicators (F-test and the Wilks Lambda) of individual age curves classification using the K-Means method as a function of the clusters number.

trees. The comparative characteristics of the sample sites are given in Table 1.

It should be noted that site Z is influenced by close proximity of cities (Abakan, Minusinsk). This influence is expressed in the local increase in temperature of 1–1.5°C during the cold period and in high anthropogenic impact of air pollution and recreational load. Also the microclimate of this area is made milder by the proximity of a large watercourse, the Yenisei River. This is manifested by a decrease in the range of variability of temperatures, and by an increase of precipitation.

Collection, transportation and primary processing of the cores were carried out according to standard procedures adopted in dendrochronology (Cook and Kairiukstis 1990). The measurements were performed with the measuring station LINTAB 5, using a specialized package TSAP Win (Rinn 2011). The dating of the samples (determination of the calendar year for each ring) was confirmed using the cross-correlation analysis in the specialized software COFECHA (Holmes 1999). In order to extract the climate signal that influences the width of an annual ring, a standardization (indexing) procedure was carried out using the ARSTAN software (Cook and Krusic 2005). During the standardization process for individual series, two steps were taken. The first removes the age trend. To describe the age trend A we used negative exponential and linear functions of the following form (Cook and Krusic 2005):

$$A(t) = a \cdot e^{-b \cdot (t+p)} + d, \tag{1}$$

$$A(t) = c \cdot (t+p) + d, \tag{2}$$

where t is age of tree estimated from individual series, a, b, c, d are numeric parameters of the functions, selected separately for each individual series, and p is pith offset to account for missing inner rings, which is estimated from the curvature of the most inner ring of core.

In order to select groups of trees with similar competitive strength, we calculated individual functions of the age trend for the first 100 years of the tree life (when the difference between the trees is the greatest). Actual annual values of functions were taken from file of age curves created in ARSTAN during the standardization, and values missing in this file were calculated by formulas (1) and (2) with parameters also obtained in ARSTAN. Then we calculated moving average values of the age trends using a window width of 10 years and without overlap, up to 10 values for each tree. Subsequently two types of cluster analysis were conducted using these moving average values of age trend for the entire regional sample of trees. Initially, in order

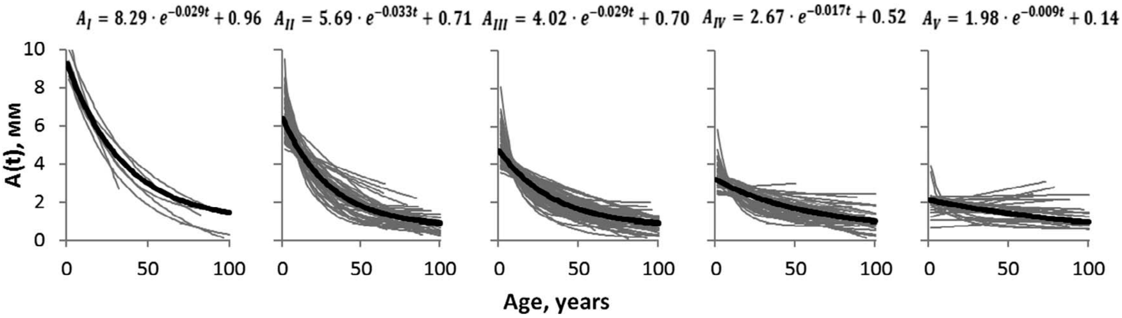
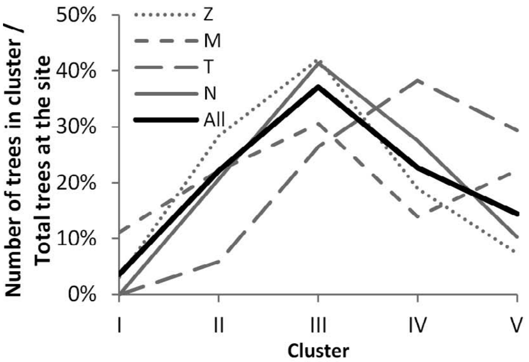


Figure 4. Classification results: individual annual age curves and average age trend functions for each cluster.

to assess the possibility for such a division we used the hierarchical classification with complete linkage as linkage criteria and Euclidean distance as metric (Figure 3a). The dendrogram indicates that the data can be separated into distinct groups. However, the possible number of groups remained unspecified, and therefore further cluster analysis was conducted using the method of K-means with the cluster number from 3 to 8. Discriminant analysis of clusters showed that for 3 and 4 clusters, the quality of classification is not sufficiently high (Figure 3b). As the number of clusters is increased from 5 to 8 the quality increases slightly. On the other hand, this reduces the volume of the cluster samples, and therefore we selected 5 as the optimal number of clusters for the available sample. Results of these two methods of clusterization are almost the same (for about 98% of trees). Earlier a similar method, *i.e.* a combination of hierarchical classification method and the method of K-means, was used in dendroclimatology to separate trees at the local level into three groups with positive, negative and insignificant climate response (Wilmking *et al.* 2004, 2005). To verify the results of the classification, we carried out a calculation of the average exponential function by formula (1) without pith offset of the age trend for each cluster sub-set of trees from individual annual values of the age trend functions. The resulting graphs and functions are shown in Figure 4. Clearly apparent are the differences between the clusters in all numeric parameters of average age functions. Clusters were numbered in the decreasing order of all these parameters.

Figure 5 shows that at each sampling area there are trees from different clusters and the distribution is close to normal (the Shapiro-Wilks criterion is significant at $p < 0.005$). At sites N and T, no data series are assigned to cluster I. Moreover, at the site T the distribution is shifted towards IV-V clusters. On site M there is an increased proportion of the extreme (I and V) clusters. On the second step of standardization, we



Site	Cluster					In all	Shapiro-Wilks' W test
	I	II	III	IV	V		
Z	3	27	40	18	7	95	W=0.8913 *p*=0.0000
M	4	8	11	5	8	36	W=0.8963 *p*=0.0027
T	0	2	9	13	10	34	W=0.8627 *p*=0.0005
N	0	6	12	8	3	29	W=0.8804 *p*=0.0034
All	7	43	72	44	28	194	W=0.9039 *p*=0.0000

Figure 5. Distribution of individual series by clusters.

Table 2. Statistical characteristics of standardized (residual) local and regional chronologies.

Characteristics	Local and Regional Chronologies				
	M	T	N	Z	All
Duration of the chronology, years	167	100	142	133	167
Number of trees, N	36	34	29	95	194
Age of the trees, years	21–167	40–96	39–142	31–133	21–167
Standard deviation, SD	0.19	0.19	0.20	0.28	0.20
Sensitivity coefficient, C	0.22	0.23	0.24	0.33	0.23
Expressed population signal, EPS	0.88–0.98	0.96–0.97	0.92–0.96	0.99	0.97–0.99
Average inter-series correlation coefficient, R-bar	0.44–0.51	0.44	0.40–0.48	0.56–0.62	0.41–0.47

performed removal of the autocorrelation dependence and obtained averaged (site – Z, M, T and N, cluster – I … V, and regional – All) residual ARSTAN chronologies (Cook *et al.* 1990).

To assess the possibility of using tree-ring chronologies in dendroclimatological analysis, we used their statistical characteristics, including standard deviation (SD) and coefficient of sensitivity C (Fritts 1976; Shiyatov 1986), which are calculated for the entire span of the chronology, and expressed population signal EPS and inter-series average correlation coefficient R-bar calculated for a window of 50 years with a shift of 25 years. Climate response is identified by the correlation analysis – using the values of paired correlation coefficients of local, cluster and regional residual chronologies with monthly temperature and amount of precipitation (from September of the previous year to August of the current year). Calculation of the statistical characteristics of tree-ring chronologies, cluster and correlation analysis were performed using software ARSTAN, STATISTICA 10 (StatSoft 2013) and Microsoft Excel 2007.

Table 3. Pearson correlation coefficients between the regional and local chronologies for the period 1915–2012 (the corresponding local chronology data were not removed from "All" prior to the analyses).

	M	T	N	All
Z	0.633	0.589	0.656	0.952
M		0.895	0.776	0.819
T			0.700	0.767
N				0.810

RESULTS

Analysis of Local Chronologies

For local and regional residual chronologies we obtained statistical characteristics that are presented in Table 2. For all of the chronologies EPS exceeds the threshold value of 0.85, inter-series correlation coefficients are significant at $p < 0.005$. The correlation coefficients between local chronologies are high (Table 3), and the maximum correlation is observed between M and T, whereas chronology Z is correlated with others to a lesser extent.

At each site, the sample is represented by trees of different ages – from 21 to 167 years in the whole area. For all areas the age structure of the sample is approximately the same (Figure 6a), except area T, where no trees older than 100 years are present in the sample.

Analysis of the correlation coefficients of the regional and local chronologies with climate variables (Figure 7) shows the negative influence of temperature of the end of the previous growing season (September of the previous year) and most of the current season (May-August). In contrast, February temperature is positively correlated with the variability of growth. Additionally, precipitation positively impacts the growth of the annual ring in Fall of the previous season (September, November), February and May-July.

Analysis of Cluster Chronologies

Statistical characteristics of the cluster chronologies are shown in Table 4. The basic statistical characteristics, standard deviation, coefficient of

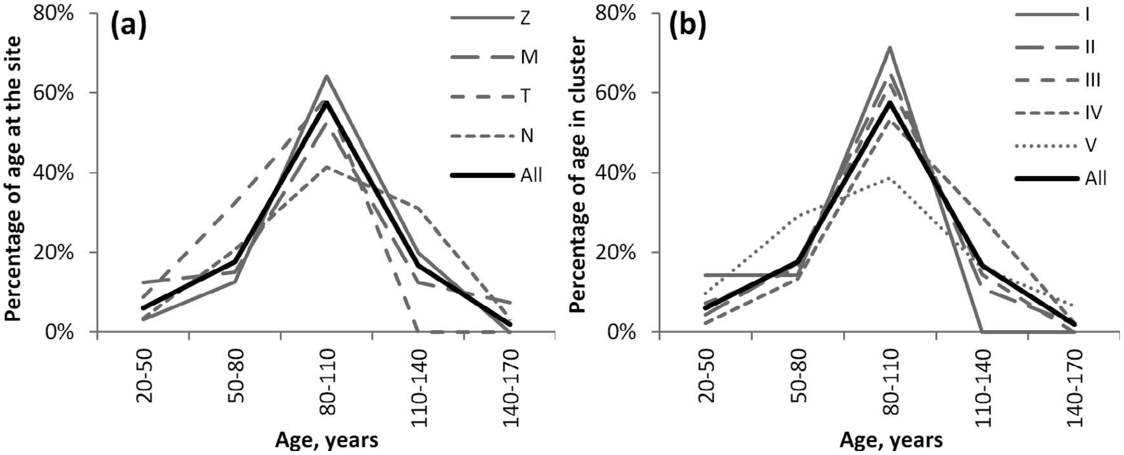


Figure 6. The age structure of the regional, local sample sets (a) and clusters (b) of trees.

sensitivity and EPS, in extreme clusters I and V are slightly lower than the medium clusters II–IV. Nevertheless, for all chronologies EPS exceeds the threshold value of 0.85, and inter-series correlation coefficients are significant at $p < 0.005$. Sample size is unequal, *i.e.* cluster V and especially cluster I are represented by a lower number of trees.

Comparison of the correlations of the cluster chronologies between each other (Table 5) shows that clusters II–IV are most similar to each other. Cluster V is correlated with others to a lesser degree, and the greatest difference exists for cluster I. In general, the differences increase with increasing “distance” between clusters. In each cluster there are trees of different ages. Differences in age structure between the clusters, except cluster I, are virtually absent (Figure 6b).

In order to identify the dependence of climate response on the competitive strength, we performed dendroclimatological analysis of cluster chronologies (Figure 8). In general, the climatic signal of the cluster chronologies is similar to the regional, but there are some differences. The negative effect of temperature of the previous year’s September and of May and June of the current year increases as the competitive strength is reduced from cluster I to cluster V (as evident

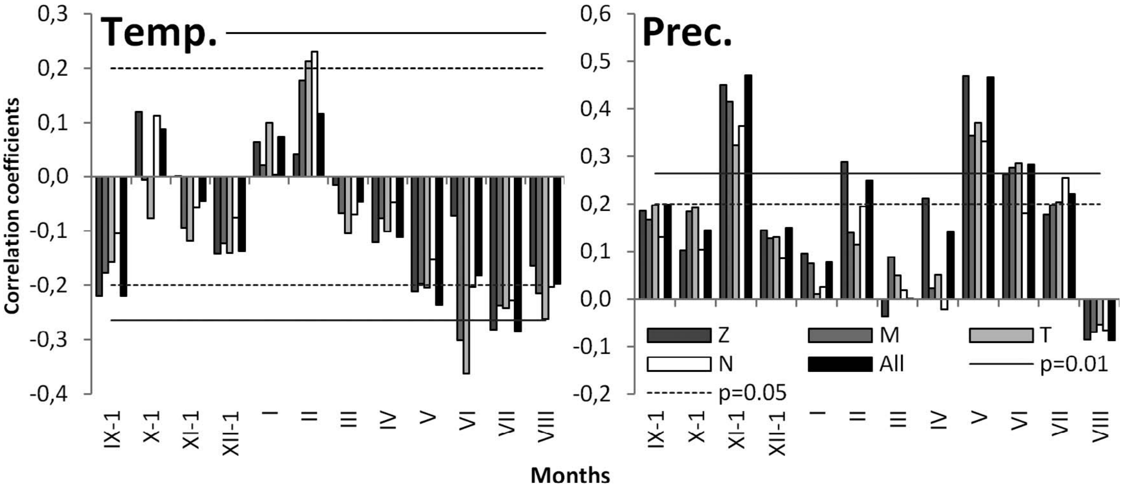


Figure 7. The correlation coefficients of local and regional chronologies with climatic variables for the period 1915–2012.

Table 4. Statistical characteristics of standardized (residual) cluster chronologies.

Characteristics	Cluster Chronologies I	II	III	IV	V
Duration of the chronology, years	101	142	126	142	167
Number of trees, N	7	46	68	44	29
Age of the trees, years	32–100	39–142	21–126	50–142	37–167
Standard deviation, SD	0.18	0.22	0.22	0.21	0.20
Sensitivity coefficient, Kr	0.21	0.24	0.25	0.25	0.23
Expressed population signal, EPS	0.87	0.92–0.98	0.97–0.98	0.96–0.98	0.85–0.95
Average inter-series correlation coefficient, R-bar	0.52	0.39–0.52	0.40–0.44	0.42–0.52	0.35–0.46

from Figure 4). In July, however, the correlation with temperature is largest for trees of cluster I. Strengthening the climate signal in slow-growing trees is also observed for precipitation of the previous September. It may be noted that there is a reduction in the impact of precipitation in February and May on the growth of trees belonging to the extreme clusters (I, V). In July, the hottest month, strong reaction of growth to precipitation stands out for cluster I.

DISCUSSION

The tree-ring chronologies (local and cluster) used in this study contain a common external signal, as indicated by their statistical characteristics. However, the values of the inter-series correlation coefficient are lower than those typically observed in regions where there is only one dominant limiting factor (Shiyatov 1973). This may be due to the presence of several climatic factors in the forest-steppe zone that significantly affect tree-ring width (TRW). Another contribution may be caused by the strong influence of non-climatic external factors, *e.g.* local conditions and competition (Magda and Vaganov 2006; Babushkina *et al.* 2011). Nevertheless, the sample replication was in all cases sufficient for dendroclimatological analysis, as pointed out by the high values of EPS.

Climate response in the radial growth of pine is complex, typical for the forest-steppes of Central Asia (*e.g.* Knorre *et al.* 2010). The amount of precipitation in May-June of the current season has a direct positive impact on TRW. In this region, November is the period of the first frosts and setting of the snow cover, *i.e.* precipitation of this period mainly plays a protective role and is highly significant on a regional scale. Presence of a significant correlation of the chronology Z with precipitation in April and its reduced response in July allows us to hypothesize that perhaps there is a possibility of an earlier activation of growth in pine and there is a shift of the growing season in this area. The negative effect of temperature in May-July is indirect because temperature increase leads to increased transpiration and evaporation from the soil surface, resulting in water stress on the plants. Local peculiarities of this response are associated with the water regime of the nearest watercourses and reservoirs (Yenisei River and small water bodies in the sampling area of N), which serve as an additional source of moisture when the water level is high. The significance of temperature and precipitation of September of the previous year (*i.e.* after the completion of growth processes) is explained by the possibility of accumulating moisture in the soil and its subsequent use in the Spring.

Comparison of average function parameters and the total set of age curves grouped in clusters (Figure 4) showed that each cluster really contains

Table 5. Pearson correlation coefficients between cluster chronologies for the period 1915–2012 (the corresponding local chronology data were not removed from "All" prior to the analyses).

	II	III	IV	V	All
I	0.736	0.715	0.733	0.724	0.759
II		0.969	0.935	0.846	0.977
III			0.960	0.882	0.987
IV				0.927	0.983
V					0.921

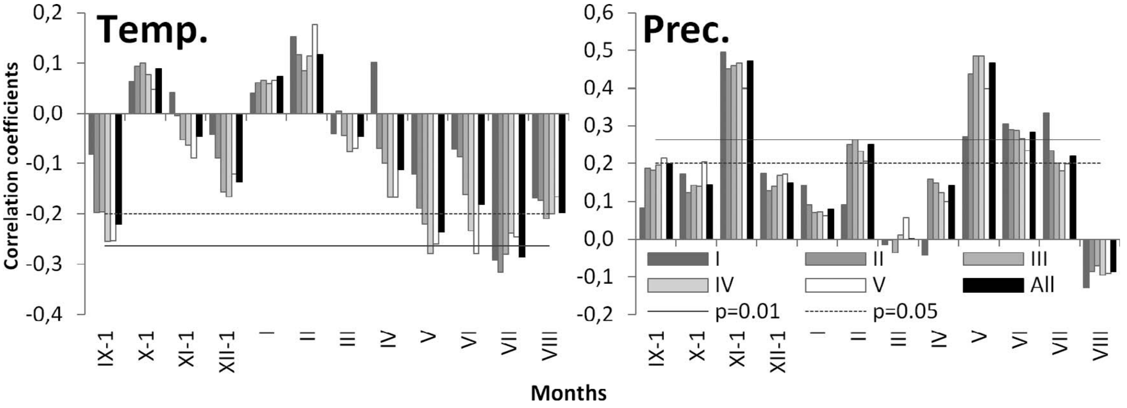


Figure 8. The correlation coefficients of cluster chronologies with climatic variables for the period 1915–2012.

trees with similar competitive strength. For example, a few trees are grouped in cluster I, which are characterized by the maximum competitive strength for the region, sharply differing from other clusters (for them the differences between adjacent clusters are much smaller). Trees with the lowest competitive strength enter in cluster V. For these trees, a significant contribution to the external signal is provided by the phytocenotic influence (competition) and peculiarities of microrelief. Our classification, based on the parameters of age trend functions, really reflects the competitive relationship of the trees between one another. Our findings are consistent with the results on research of thinning and stand density effects on the growth rate of individual trees (Blasing *et al.* 1983; Franklin *et al.* 2009).

The analysis of the distribution of trees into clusters for each sampling site (Figure 5) shows that the deviations of these distribution from normal depend on the sample size, *i.e.* the Shapiro-Wilks' criteria of normality is more significant for large (Z and All) than for small samples. The shift of the distribution towards low competitive strength is observed for sampling sites with more extreme local conditions, *e.g.* smaller amount of soil moisture caused by the greater distance from water bodies (M, T) and the location of the sampling site on the slope of a steep hill (T). Thus, the characteristics of the distribution of local samples by clusters are correlated with habitat conditions, but its common regional pattern represents competitive relationship between trees.

Cluster chronologies, as well as local chronologies, contain a common climatic signal (Table 4). Relatively low values of the sensitivity coefficient may be caused by the pooling of trees from different local growing conditions into one sample. Significance of the influence of local growing conditions in the forest-steppe zone has been shown by the authors earlier (Babushkina and Belokopytova 2011; Babushkina *et al.* 2011). Chronologies of clusters I and V are characterized by a lesser degree of similarity with others (Table 5) and lower values of the statistical characteristics (SD, EPS), which can be associated with a smaller sample size, as well as with the interaction of climatic and phytocenotic (competitive) factors. The strongest trees, for which the effect of competition is minimal, are more resistant to the influence of climatic variables, which leads to the weakening of the climatic signal (Van Den Brakel and Visser 1996). For weak and suppressed trees the influence of phytocenotic factors becomes comparable in strength to the climatic factors. It adds noise to the common signal, which leads to the lower sensitivity of chronologies, as pointed out, for example, in Martín-Benito *et al.* (2008). Therefore the climatic response is the most stable for intermediate clusters (II–IV).

Previously, the differences in climate response were shown for other growth conditions for trees classified by the class of the crown or by the trunk diameter, *i.e.* by the volume of the living space and respectively by the availability of resources (Martín-Benito *et al.* 2008; Campelo *et al.* 2013). Such differences are observed in the forest-steppes of South Siberia too, *e.g.* the strengthening of the negative temperature impact in the first half of the season and of the climate in the previous September at low competitive strength is related to the decrease in the availability of soil moisture related to the smaller volume, branching and depth of the root system. In July there is a reduction of the influence of temperature and precipitation associated with a decrease in the growth rate of the trees. This is related to the differences in the timing of cambial activity (Rossi *et al.* 2008). For example, for our study area the cell division ends approximately at the end of July (Babushkina *et al.* 2010), but for slower growing trees this process ends earlier. Because radial growth is mostly determined by the cell number and accordingly depends on climatic conditions during the period of cell division (Babushkina and Belokopytova 2011; Vaganov *et al.* 2011), the dominant trees show a more significant climatic response in July. Nevertheless, for all the clusters there is a general pattern of regional climate signal.

Thus, in the conditions of the forest-steppe zone, the complex climatic signal is most fully expressed in the intermediate clusters II–IV, but for some climate variables it is more appropriate to consider the response of the extreme cluster chronologies, *e.g.* the fastest-growing trees (cluster I) have a stronger response to precipitation in July, the slowest-growing trees (cluster V) have a stronger response to the temperature in May-June and climate of the previous September. Thus, for a detailed study of the climate signal and for dendroclimatological reconstructions, one can use separate sub-samples of the trees, which are classified by the competitive strength, *i.e.* dominant (I), characterized by average position (II–IV) and suppressed (V cluster).

CONCLUSIONS

1. Classification of individual TRW series according to the characteristics of the age trend curve allows grouping trees with similar competitive strength. This reflects phytocenotic relations in the tree stand. Statistical characteristics of the cluster generalized chronologies depend on their living area and sensitivity to external factors.
2. TRW chronologies of Scots pine in the forest-steppe zone of South Siberia contain a common complex climatic signal, caused primarily by the moisture-reducing influence of temperature in May-September, as well as the positive impact of precipitation in May-July and September of the previous year as a source of moisture, and November and February when snow cover acts to protect the root system from frosts.
3. Climate response varies depending on the competitive strength. The moisture-reducing influence of summer temperatures is more strongly expressed in the variability of growth of the lowest tree clusters, the root system of which has a smaller volume and is more sensitive to the lack of moisture. In July, the timing of the cambial activity period, which is also determined by the competitive strength, influences the climate response.
4. The changes of the climatic response caused by local conditions and by competitive strength have the same scale. Therefore, both these changes can be considered in improving the quality of dendroclimatological reconstructions. In order to account for the competitive strength during reconstruction, it can be useful to choose clusters that have the most stable climatic response for physiological reasons and competition. There are, as shown here, clusters characterized by average competitive strength.

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