ISSN 1067-4136, Russian Journal of Ecology, 2014, Vol. 45, No. 5, pp. 325–332. © Pleiades Publishing, Ltd., 2014.
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Climatic Signal in Radial Increment of Conifers in Forest-Steppe of Southern Siberia and Its Dependence on Local Growing Conditions

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Received September 10, 2013

Abstract—Radial increments have been studied in Siberian larch (*Larix sibirica* Ledeb.) and Scots pine (*Pinus sylvestris* L.) growing in the forest–steppe zone of southern Siberia in areas with different landscapes and levels of soil moisture supply but uniform climatic conditions. It has been shown that the radial increment significantly depends on climatic factors, primarily temperatures in April to July and September, sums of precipitation in April to July and September to November, and hydrothermal coefficient in May. The climatic response in the wood of conifers in the forest–steppe zone differs depending on their species-specific features and local growing conditions.

Keywords: radial increment, tree-ring width, climatic factors, soil moisture, forest-steppe zone

DOI: 10.1134/S1067413614050038

Increasing concern in current climate change has stimulated research on the effect of various factors on ecosystem dynamics. A promising direction in this field is dendroecological analysis, i.e., the study of characteristics of wood as indicators of environmental conditions. The task of revealing an environmental signal in wood is simple when the growth and development of plants are limited by a single extreme factor. Thus, detailed data have been obtained on the effect of temperatures in the first half of the growing season at the upper and northern forest limits and of precipitation in highly arid regions (Naurzbaev et al., 2003; Briffa et al., 2004; Sidorova et al., 2007; Esper et al., 2010). However, most forest ecosystems are located in areas with more favorable conditions, where the effects of several factors are significant. This concerns not only climatic but also local factors such as topography, soil types, the regime of ground and surface waters, etc. For example, recent studies performed in Siberian taiga ecosystems concern the effects on tree-ring width of the pattern of permafrost landscapes (Nikolaev et al., 2011), soil moisture (Velisevich and Khutornoi, 2009), and landscape heterogeneity (Kuznetsova and Kozlov, 2011; Tabakova et al., 2011). The forest-steppe zone has been less studied in this respect, although publications are available on dendroclimatic analysis of TRW in Scots pine in the Southern Urals (Agafonov and Kukarskikh, 2008) and the climatic response in the increment of pine (Magda and Vaganov, 2006) and larch (Knorre et al., 2010) in the Altai–Sayan mountain region. The results of all these studies confirmed that the main climatic components have a complex influence on the radial increment of conifers.

In 2008, dendroecological studies were started in the Republic of Khakassia, where a wide diversity of vegetation zones, forest-forming tree species, and landscape types is observed in a relatively small territory. A dendrochronological station (DS) was established in the forest–steppe zone, which included two habitats with contrasting landscapes and soil moisture regimes. Studies on the dynamics of radial increments in Scots pine, Siberian larch, and Siberian spruce at this station have shown that they depend on precipitation and temperature in the first half of the growing season, but the effect of these factors strongly differs depending on local growing conditions and species-specific features of trees (Babushkina et al., 2010, 2011). These studies were expanded in 2012, when the Laboratory of Biogeochemistry of Eurasian Ecosystems was organized at Khakass Technical Institute—Branch of Siberian Federal University and several more DSs were established in the republic and southern Krasnoyarsk krai.

The purpose of this study was to compare the effect of local conditions on the radial increments of two conifer species differing in certain physiological and ecological features but growing under uniform climatic conditions.

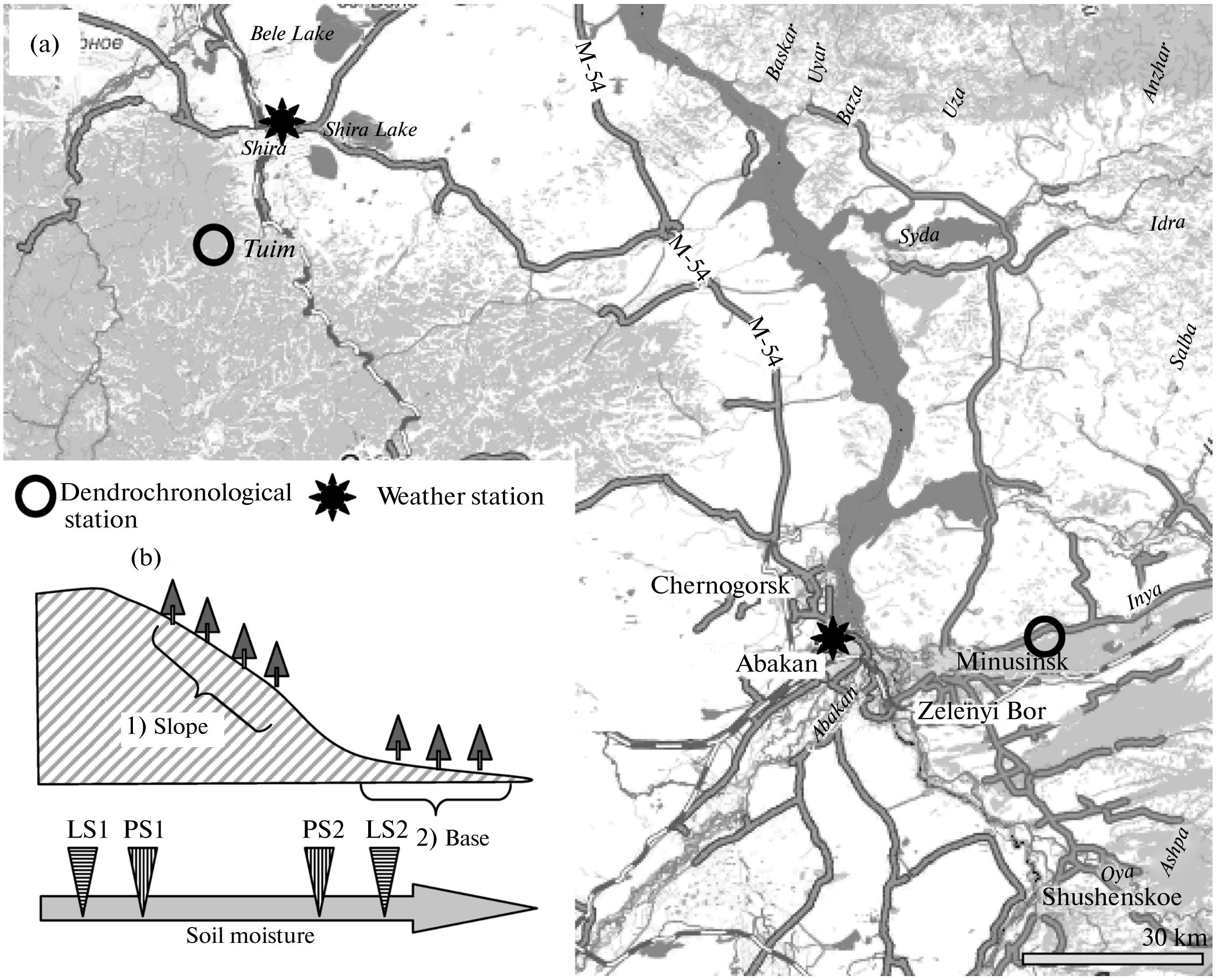

Fig. 1. (a) Map of study region (Republic of Khakassia and southern Krasnoyarsk krai) and (b) scheme of wood sampling at dendrochronological stations and relative positions of sites in a provisional gradient of soil moisture.

MATERIAL AND METHODS

Materials for dendroecological analysis were obtained from two DSs in the Minusinsk depression, southern Siberia (Fig. 1a). DS Berenzhak (54°20′ N, 89°44′ E) is in the south of Chulym–Yenisei Hollow, 32 km southwest of the village of Shira (Shira weather station, #29756; 54°30′ N, 89°56′ E). DS Malaya Minusa (53°45′ N, 91°56′ E) is at the edge of a belt pine forest in the north of Minusinsk depression, 15 km east of the city of Minusinsk (Minusinsk–Opytnoe Pole weather station, #29866; 53°41′N, 91°40′E). Small distances between DSs and weather stations contributed to the quality of dendroclimatic data.

With respect to climatic zoning, the study area is in the Altai–Sayan region of the temperate belt, with moderately cold continental climate (Alisov, 1956). According to data from the Shira weather station, the annual average air temperature is about 1°C. The onset of the growing season (when daily temperatures rise above 5°C) takes place in the last ten-day period of April. The period with temperatures above 10°C is 110–120 days. Annual average precipitation is 290 mm; 86–94% of this amount falls during the warm season (April–October), with a peak in July and a minimum in February to March (Fig. 2). The climate in Minusinsk is slightly different: the annual average temperature is the same, but winters are 1–2°C warmer and summers are 1°C cooler; annual average precipitation is 330 mm, with the summer peak being lower (81–91% in April to October) due to more snowy winters. However, these differences are minor and allow adequate comparison between the two areas. We used monthly data from weather stations on air temperature in the near-ground layer and total precipitation for 1924 to 2008 and calculated monthly values of Selyaninov's (1937) hydrothermal coefficient (HTC) in May to August.

Samples at each DS were collected in two different habitats: (1) a steep slope (about 20–30 degrees) of

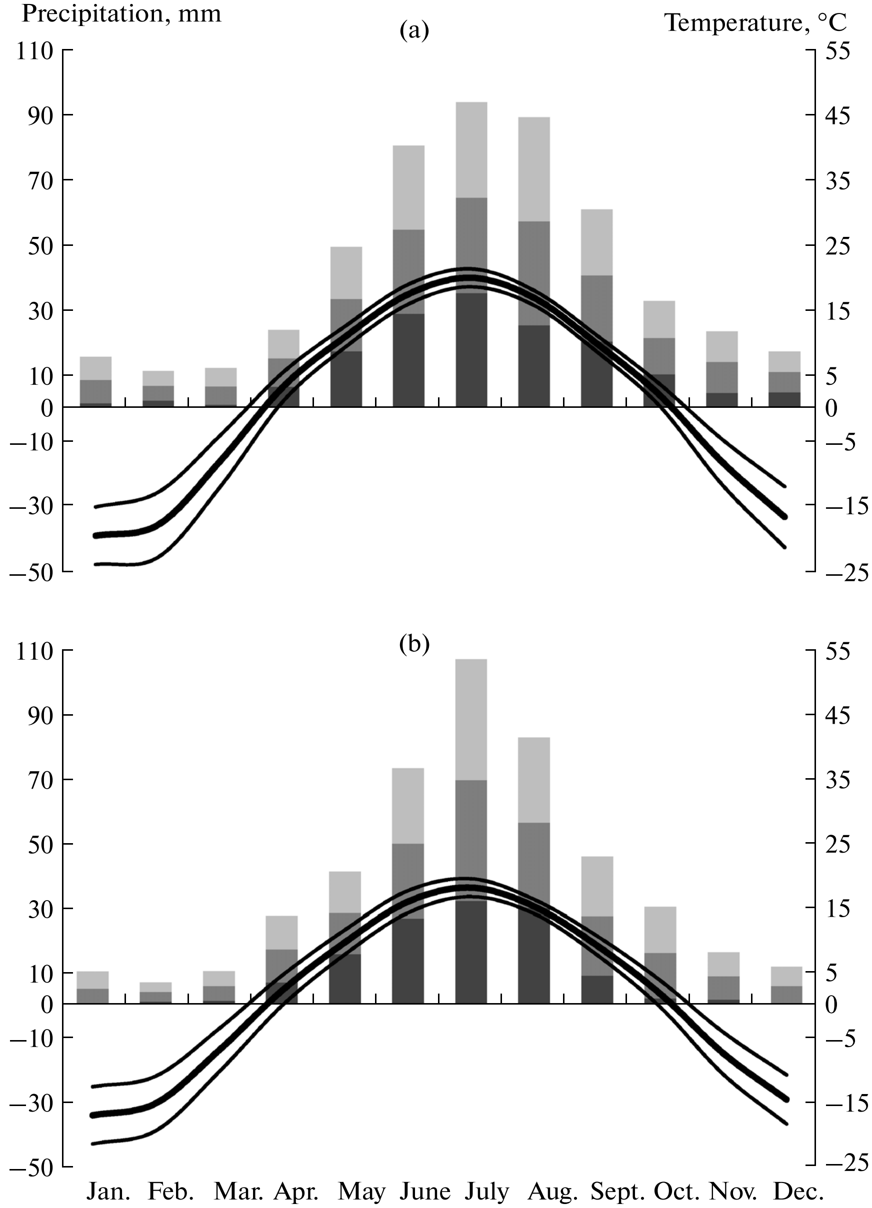

Fig. 2. Climate graphs from (a) Minusinsk and (b) Shira weather stations for monthly average temperatures (lines) and precipitation (bars) over the period from 1915 to 2012. Top and bottom lines and bars show standard deviations.

southern exposure, and (2) the floodplain of an intermittent stream at its base, with a relatively high groundwater table (Fig. 1b). At DS Berenzhak, the slope is covered with grass–herb pine–larch forest with birch growing on mountain gray forest soil with underdeveloped profile and rock outcrops; the floodplain site is a forest–steppe area where forest is represented by sedge–moss spruce stand with shrubs and single larch and birch trees, on podzolized meadow chernozem soil. At DS Malaya Minusa, both site are covered with grass–herb birch–pine forest on poorly developed, stratified aeolian-humus chernozem soils; on the slope, the soil is rich in sand, and the understory is relatively sparse; in the floodplain site, the moss layer is noticeable (up to 30% coverage). Thus, plots with contrasting conditions of moisture supply were selected at both stations, especially at DS Berenzhak. Figure 1b shows relative positions of the sites in a provisional gradient of soil moisture as estimated from the composition of vegetation and specific features of soils and landscape.

Variation in radial increment was studied in two tree species: Siberian larch (*Larix sibirica* Ledeb.) at DS Berenzhak and Scots pine (*Pinus sylvestris* L.) at DS Malaya Minusa. Core samples were collected, transported, and processed by standard dendrochronological methods (Shiyatov et al., 2000). Measurements were made in a LINTAB 5 semiautomatic

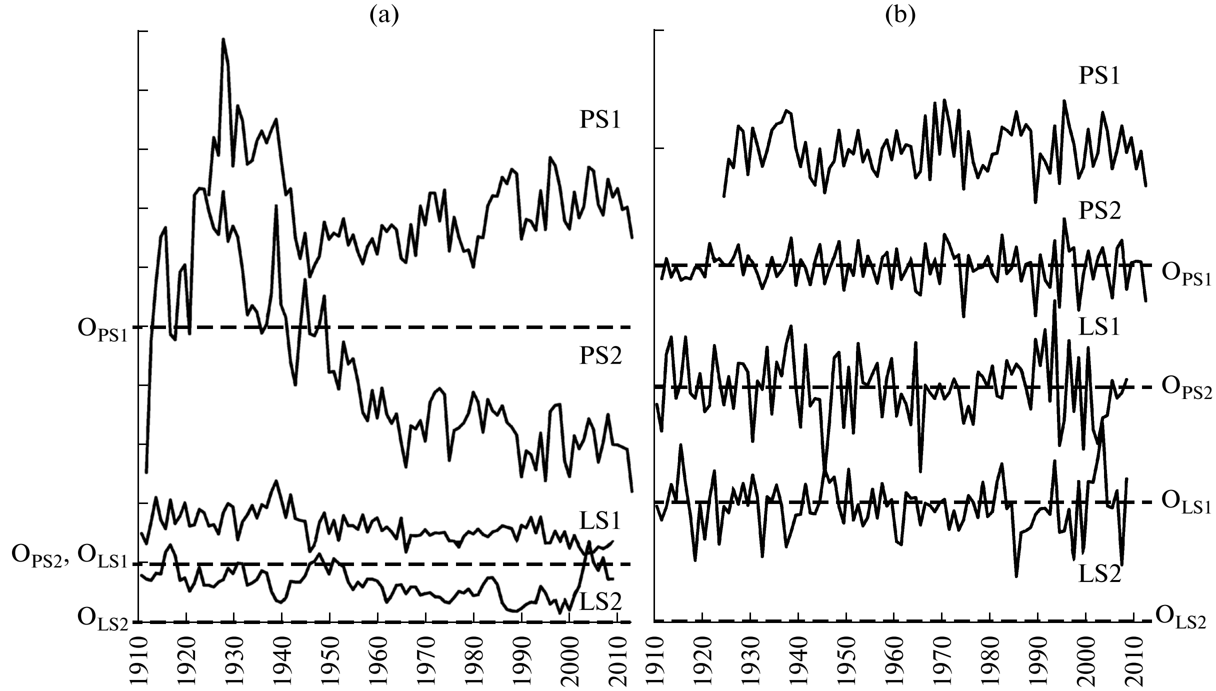

Fig. 3. Local (a) measured and (b) indexed chronologies of tree-ring width over the period from 1910 to 2012. Vertical grid step (a) 1 mm, (b) 1. For clarity, chronologies are shifted relative to each other along vertical axis, and zero values are indicated.

device with the TSAP Win program package, to an accuracy of 0.01 mm (Rinn, 2011). Sample dating (calendar years determined for individual tree rings) was verified by cross-correlation analysis with the COFECHA program. To reveal the climatic signal influencing tree-ring width (TRW), the standardization (indexing) procedure was carried out. Using the ARSTAN program, we first eliminated the impact of tree age trend (estimated using a negative exponential and a linear functions) and then eliminated autocorrelation; thereafter, individual indexed increment curves were averaged to obtain a local chronology (Shiyatov et al., 2000). Calculations of statistical characteristics of tree-ring chronologies, correlation analysis, and analysis of differences between the samples for statistical significance were performed with programs STATISTICA 10 (StatSoft Russia, 2013) and Microsoft Excel 2007.

RESULTS AND DISCUSSION

We obtained four measured and indexed local chronologies: two for larch, on the slope (LS1) and in the floodplain (LS2), and two for pine (PS1 and PS2, respectively) (Fig. 3). Analysis of their statistical parameters has shown that the radial increments of both species in sites with higher soil moisture are greater, as follows from both maximum and average TRW values (Table 1). Thus, the significance of this factor for the processes of wood formation is obvious. Tree rings in pine are wider than in larch, which is explained by younger tree age and longer period of xylem formation during the growing season (Babushkina et al., 2010).

Higher standard deviations and variation coefficients recorded in floodplain plots are indicative of a wider range of variation in TRW, but the effect of external factors is stronger on the slopes (were the coefficient of sensitivity is higher); i.e., variation in the floodplain is largely caused by internal and phytocenotic factors.

Coefficients of correlation of individual chronologies with the local chronology, signal-to-noise ratio, and expressed population signal are traditionally used to reveal the presence of an external signal and determine if a chronology is suitable for dendrochronological research (Cook, 1985). In our case, the values of all these parameters are sufficiently high for both measured and indexed chronologies.

Analysis of similarity between the indexed chronologies with regard to the significance level of correlation coefficients have shown that the strongest correlations exist between chronologies from the two sites at the same DS, especially between pine chronologies from DS Malaya Minusa ($p < 0.0005$), where habitat conditions in the plots are less contrasting than at DS Berenzhak (Table 2). A positive correlation is also observed between pine and larch chronologies from the slopes, but it is less significant because of species-specific differences in climatic response and spatial separation of the plots. However, such a correlation is

Table 1. Statistical parameters of tree-ring chronologies

Parameter	LS1	LS2	PS1	PS2
General				
Duration, years	272	165	89	105
Period, years	1737–2008	1844–2008	1924–2012	1911–2012
Number of trees	14	10	12	17
Total number of tree rings	2138	1331	793	1319
Measured chronologies				
Minimum value, mm	0.130	0.169	0.850	1.216
Maximum value, mm	1.830	2.880	4.875	6.349
Mean value, mm	0.721	0.781	2.076	3.252
Standard deviation, mm	0.330	0.476	0.769	1.372
Coefficient of variation	0.458	0.610	0.370	0.422
Coefficient of sensitivity	0.296	0.234	0.202	0.169
Average coefficient of correlation with local chronology	0.727	0.713	0.649	0.698
Signal-to-noise ratio	20.45	8.92	5.67	12.64
Expressed population signal	0.953	0.899	0.850	0.927
Indexed chronologies				
Standard deviation	0.281	0.228	0.198	0.374
Coefficient of sensitivity	0.325	0.252	0.228	0.229
Average coefficient of correlation with local chronology	0.739	0.634	0.704	0.630
Signal-to-noise ratio	14.08	4.98	10.93	10.65
Expressed population signal	0.934	0.853	0.916	0.914

Table 2. Relations between indexed local chronologies

Parameter	LS1/LS2	PS1/LS1	PS1/LS2	PS2/LS1	PS2/LS2	PS1/PS2
Correlation coefficient	**0.186***	0.205	–0.048	0.009	–0.078	**0.674**
Duration of the comparison period, years	**165**	85	85	101	101	**89**
Significance level	**0.017**	0.060	0.665	0.928	0.441	**0.000**

* Boldfaced values of correlation coefficient are statistically significant at $p < 0.05$.

absent under higher soil moisture, which is evidence for optimization of local conditions and consequent attenuation of common signal (Fritts, 1976; Shiyatov, 1986; Vaganov et al., 2006). Chronologies from different tree species growing in different habitats are not correlated with each other, despite uniformity of climatic conditions; i.e., the TRW response to climate in the forest–steppe zone is very strongly dependent on local conditions and species-specific features of trees.

This response was evaluated primarily by correlation analysis with monthly values of temperature and precipitation (Fig. 4).

The climatic signal in pine chronologies from DS Malaya Minusa is generally similar, but correlations with temperature and precipitation are stronger on the slope, where the groundwater table lies deep beneath the surface and the sole source of moisture is precipitation, which has a significant effect on the radial

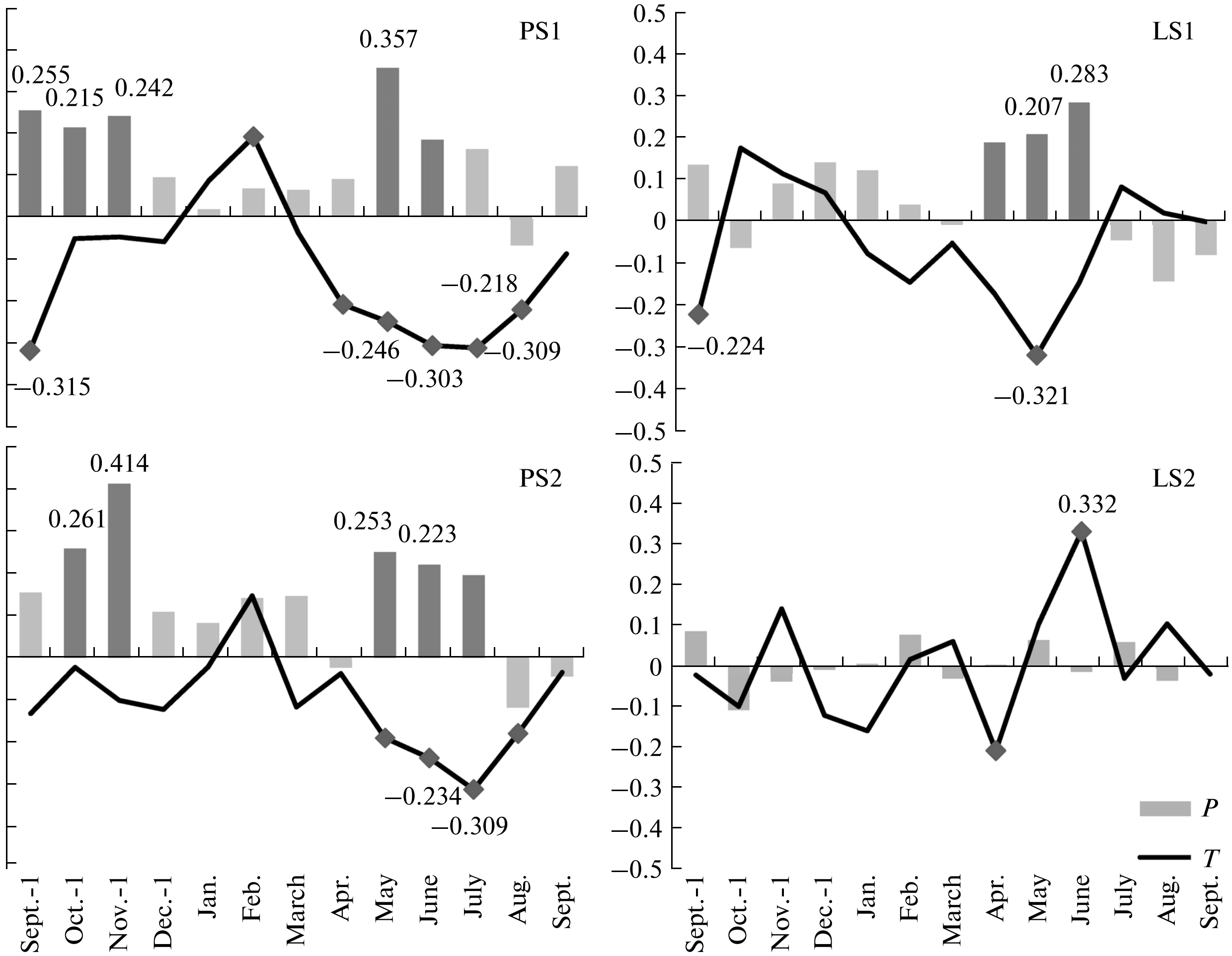

Fig. 4. Coefficients of correlation of tree-ring chronologies with monthly average temperature (*T*) and precipitation (*P*) over the period from 1924 to 2008 (common to all chronologies). Coefficients significant at $p < 0.10$ are indicated with dark bars and markers; values are shown for coefficients significant at $p < 0.05$.

increment in the first half of the growing season, especially in May. At the same time, the rise of temperature during the greater part of the season enhances evaporation from the soil surface and transpiration, which leads to water stress and consequent inhibition of xylem formation. The hydrological regime at the base of the slope is different due to rainfall runoff from the slope and drainage through permeable sandy soil, relatively shallow groundwater table, and proximity to the Minusinka River. Hence, the effect of precipitation and temperature is weaker than on the slope in the first half of the growing season but becomes stronger in July, upon natural drop of the groundwater table and water level in the river. The amount of precipitation in previous October–November has an effect as a factor determining the depth of snow cover, which insulates tree root systems in winter and serves as a source of moisture at the beginning of the growing season. A positive, although not highly significant (0.071) correlation is observed between TRW in pine growing on the slope and the average temperature in February, the coldest month (Fig. 2). A probable explanation is that snow depth on the slopes is relatively low, since it is blown off by the wind, and the root systems of pine can suffer frost damage in hard winters.

An important factor for trees on relatively dry and less fertile soil on the slopes is accumulation of assimilates, which continues until the end of September. Its results largely determine the rate of growth processes at the beginning of the next season, which explains a positive correlation of TRW in pine with precipitation in September. The rise of temperature in this period, as in summer, has a desiccating effect. A similar but weaker correlation is also observed for TRW in larch growing on the slope. The absence of significant correlations with autumn precipitation in this case may be explained by higher climate continentality (i.e., smaller amount of autumn precipitation) at DS Berenzhak, compared to DS Malaya Minusa, which leads to earlier cessation of assimilate accumulation. The

Table 3. Analysis of differences of HTC (May–August) for pointer years from long-term average values of HTC

Average value	HTC_{May}	HTC_{June}	HTC_{July}	HTC_{Aug}
Minusinsk weather station				
Over entire period	1.003	1.082	1.094	1.129
Over negative pointer years	**0.679*** **$p < 0.054$**	0.942 $p < 0.648$	0.821 $p < 0.118$	1.049 $p < 0.813$
Over positive pointer years	**1.439** **$p < 0.031$**	**1.527** **$p < 0.023$**	1.206 $p < 0.427$	1.172 $p < 0.801$
Shira weather station				
Over entire period	0.935	1.065	1.236	1.184
Over negative pointer years	0.704 $p < 0.178$	0.871 $p < 0.307$	1.031 $p < 0.504$	1.223 $p < 0.749$
Over positive pointer years	**1.446** **$p < 0.043$**	1.162 $p < 0.611$	1.012 $p < 0.606$	0.911 $p < 0.326$

* Boldfaced values significantly differ from long-term average values at $p < 0.10$.

positive response of TRW to precipitation during the first half of the growing season and its negative response to May temperatures in larch growing on the slope are attributable to the same factors as in pine, and a relatively low degree of their expression may be explained by adaptability of larch to different ecological conditions (Dylis, 1961; Sudachkova, 1977). Under sufficient moisture conditions, TRW in larch shows no significant correlation with precipitation but positive correlates with temperature in June, which stimulates photosynthesis and, therefore, growth processes. In April, long-term thaws often occur in the study region, promoting premature onset of vegetative growth. In the floodplain site, where soil moisture is high, subsequent frosts may result in damage to the shallow root system of larch (Vaganov and Kruglov, 2007), which explains negative correlation of TRW with temperature in April ($p = 0.052$).

Since simultaneous positive correlation with precipitation and negative correlation with temperatures in May to July, were observed in three out of the four sites, it was of interest to consider as an ecological factor one of drought indices, e.g., Selyaninov's HTC for different months of the growing season. However, correlation analysis revealed no significant relationships, and we decided to use a different approach: calculations of HTC were performed for the period from 1915 to 2012, but we selected only so-called pointer years in which rings in the majority of trees were either the narrowest or the widest (Shiyatov et al., 2000). It should be noted that the sets of pointer years for the slope and floodplain sites were practically identical at both DSs, and differences between the sites in the response to HTC variation were not evaluated. Next, we compared three samples of HTC for every month over only "positive" and "negative" pointer years. Statistically significant differences between the sample average values provided evidence for the dependence of redial increment on HTC in May and June for pine and only in May for larch (Table 3). Thus, the hydrothermal regime in May and, to a lesser extent, in June proved to be the most significant factors for the growth and development of conifers in the forest–steppe of Minusinsk depression.

The results of this study provide a basis for the following conclusions:

(1) Chronologies of the radial increment of conifers in the forest–steppe zone carry a fairly strong climatic signal on condition that conspecific trees growing under uniform habitat conditions are pooled into the local chronology. The construction of a generalized chronology under given natural conditions is inexpedient.

(2) Interspecific differences in the climatic signal from TRW decrease in dry habitats and increase under moderate moisture conditions.

(3) The most significant climatic factors for the two species growing under different habitat conditions are as follows: temperatures in April–June and September and precipitation in April–July and September–November.

ACKNOWLEDGMENTS

This study was supported by the RF Ministry of Education and Science within the framework of State Contract for Services to Siberian Federal University, no. 5.7917.2013.

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Translated by N. Gorgolyuk