Spatial classification of moisture-sensitive pine and larch tree-ring chronologies within Khakass-Minusinsk Depression, South Siberia

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Key Message

Growth patterns of Scots pine and Siberian larch under water deficit across an intermontane valley in South Siberia depend not only on landscape physiography, but on species-specific climatic sensitivity and phenology.

Abstract

The wide intermountain Khakass-Minusinsk Depression (KhMD) in southern Siberia presents an ideal setting for studying the potential impacts of a warming climate on forest ecosystems. The centre of continental Asia has one of the most intense rates of warming in the Northern Hemisphere, and the KhMD has multiple tree species of proven dendroclimatic value growing in drought-stressed environments. Investigation was aimed on spatial patterns of tree-growth and its climate response across the KhMD for two main conifer species of moisture-deficient habitats, Scots pine (*Pinus sylvestris* L.) and Siberian larch (*Larix sibirica* Ledeb.). Correlation and cluster analysis were applied to a recently developed network of 15 tree-ring chronologies. Hierarchical classifications were based on the inter-chronology correlation matrix and on correlations of chronologies with monthly climate variables. Results underscore the general influence of hot-dry conditions on reducing growth and suggest a spatial grouping of chronologies governed by physiography and modified by species-dependent ecophysiological response to climate. Both applied classifications agree in the designation of geographically oriented clusters. A purely geographic grouping is broken, however, by species-specific climate dependence and phenology in deciduous *Larix* and evergreen *Pinus*. A differential ability to utilize melting snowpack in spring is advanced as a possible explanation for chronologies abandoning physiographically defined clusters. Such inter-species heterogeneity can manifest itself in the intensity of the climate change impact on vegetation, and lead to prospects of significant species composition changes in ecosystems.

Keywords: dendrochronology; moisture-sensitive ecosystem; climate-growth relationship; spatial cluster analysis

Declarations

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Introduction

Forest ecosystems worldwide are threatened by climate impacts of global warming, which is most intense regionally in the inner part of Eurasia (Davy et al. 2017; IPCC 2019; Zhirnova et al. 2021). The harsh continental climate of this macro-region, characterized by large temperature variation, hot summers and frosty winters with little snow, increases the risk of extreme events and the vulnerability of ecosystems (Allen et al. 2010; Dai 2013). Climatic dynamics and its impact on ecosystems can be modified by local factors, such as orographic setting or land use, which have led to unique territories with distinctive climatic physiography (e.g., Cho and Kim 2021; Shen and Zhao 2021). One such area is the Khakass-Minusinsk Depression (KhMD), a large valley in southern Siberia bounded on the west by the Kuznetsk Alatau, on the south by the Western Sayan Mountains, and on the east by the Eastern Sayan Mountains (Fig. 1a). This valley, distant from oceans and in the rain shadow of surrounding mountains, receives an average of just 250-500 mm of precipitation, and is covered mainly by steppe vegetation. Due to its orographic setting, the KhMD has climatic variation coherent across its entire territory but distinct from surrounding regions. The Yenisei, one of the largest rivers in Siberia, flows northward through the valley, and contains two massive reservoirs created in the second half of the 20th century: the Krasnoyarsk Reservoir and the Sayano-Shushensky Reservoir. These reservoirs influence climate locally and to a lesser degree regionally (Savkin 2000; cf. Gyau-Boakye 2001). Their impact accentuates regional warming in the cool season (Zhirnova et al. 2021), so that ecosystem changes in the KhMD may be predictive of larger-scale shifts expected for continental Eurasia as a consequence of climate change. Forest-steppe boundaries of the KhMD and isolated forest stands located within the steppe zone provide tree-ring chronologies as a source of long-term information on ecosystems response to climate variation. Two conifer species form the lower forest border of the KhMD: Scots pine (*Pinus sylvestris* L.) and Siberian larch (*Larix sibirica* Ledeb.) (Chytrý et al. 2008). Both species are attractive for dendroclimatological studies because of a wide geographical distribution, sensitivity to climatic variables, and demonstrated coherency of growth patterns on a regional scale (Grissino-Mayer 1993). Despite comparable drought resistance, the two species are at opposite ends of the spectrum in regards to coping mechanism for water deficit (McDowell et al. 2008). Tree-ring chronologies of these species can improve our understanding of the influence of environment and ecophysiology on conifer growth dynamics in this unique region. In this study, we apply dendroclimatic and cluster analysis to a recently developed tree-ring network across the moisture-sensitive forests of the KhMD to determine spatial and species-based differences in tree growth and its climatic response.

Materials and Methods

Wood samples of Scots pine and Siberian larch were collected from habitats experiencing moisture deficit (Fig. 1a, Table 1): isolated forest in the steppe of the central part of the KhMD (sampling sites ZSH, MMIN, TAR, MNIC), forest-steppe on the valley outskirts in the foothills of the Kuznetsk Alatau (BGD, BID, KAM, KAZ) and the Western Sayan (KALY, MAY), and sub-taiga forest higher up the slope of the Western Sayan (SHB). In mountain habitats, drier south-oriented slopes were preferred for tree-ring sampling sites. Field work, sample processing and development of local residual tree-ring width (TRW) chronologies were carried out using standard dendrochronological methods (Cook and Kairiukstis 1990) using program ARSTAN (Cook et al. 2007). During standardization, age trends were removed from measured ring widths by fitting either a negative exponential curve or a linear function. The latter was used automatically for individual core series where decline of TRW with age was inconsistent with negative exponent. Autocorrelation was removed from the indices by autoregressive modeling, followed by averaging of indices over cores to form site chronologies. The strength of the common signal within each chronology (Table 1) was summarized by *r-bar*, the average inter-series correlations (Cook and Kairiukstis 1990).

To summarize climate variations, monthly time series of average air temperature and total precipitation for meteorological stations Tashtyp (52.80° N, 89.55° E, 455 m a.s.l., 1936-2014), Minusinsk (53.72° N, 91.10° E, 255 m a.s.l., 1936-2014), and Cheryomushki (52.83° N, 91.38° E, 330 m a.s.l., 1951-2014) were obtained from the All-Russian Research Institute of Hydrometeorological Information, World Data Centre (RIHMI-WDC; http://meteo.ru/data).

The climatic response of TRW was analyzed by pairwise Pearson correlations of chronologies with monthly precipitation and temperature series at the station nearest the sampling site (as marked by dashed lines on the map in Fig. 1a). Hierarchical cluster analysis, using the Ward method to agglomerate clusters (Ward 1963; Wilks 2019), was applied to classify tree-ring chronologies. The Ward method was selected to minimize within-cluster variation (i.e., increase similarity between all chronologies belonging to cluster) and provide compact clusters (Hands and Everitt 1987). Two applications of this analysis were performed using different distance measures: 1) inter-chronology correlation matrix (i.e., distance between each two chronologies is measured as $1-r$, where r is the correlation between this pair), and 2) correlations of chronologies with climatic factors as initial “coordinates” of chronologies, and squared Euclidean distance as the metric of distance appropriate for Ward method (Wilks 2019). In the first cluster analysis application (Fig. 1b), input data were the pairwise Pearson correlations between chronologies over 1936-2014 (slightly less for the shortest chronologies from sites KALY and MAY). In a second cluster analysis application (Fig. 1c), input data were sets of 28 correlation coefficients between each TRW chronology and monthly precipitation and temperature series from July of the previous year to August of the growth year (biological year).

Results and Discussion

TRW site chronologies range in length from 66 to 316 years (Table 1). The mean between-tree correlation of detrended ring-width series (*r-bar*) ranges from 0.31 to 0.56, which is relatively high for climate-sensitive chronologies (cf. Ljungqvist et al. 2020). Correlations of chronologies between sites and/or species also reveal a strong commonality in the dynamics of radial growth supportive of a climate response. Between-chronology correlations are all positive. Most are significant at $p<0.05$, but they range from 0.09 to 0.95, depending on proximity of the sites, as well as on the local natural conditions (e.g., soil, slope, drainage) and the species-specific physiology and phenology of pine and larch.

The contribution of geographic distance to the differences between chronologies is explained by both the high spatial heterogeneity of the precipitation field and the altitudinal-latitudinal gradients of temperature and precipitation, which drive shifts in the seasonality of the climatic response. In the middle of the KhMD, in the large isolated forest called “Minusinsky Bor,” with a small range of elevation and relatively homogeneous aeolian soils, similarity between pine chronologies is high and correlations range from 0.63 to 0.95. The intensity of the climatic response is modulated by differences in forest settings: isolated forest in the steppe zone with minimal amount of precipitation, versus forest-steppe and more humid subtaiga zone. Within-site correlations between pine and larch

TRW chronologies range from 0.55 to 0.73. These high correlations are explained by the common requirements of both conifer species for moisture at the semi-arid boundary of their distributions, as well as by common local conditions and climatic variation.

Fundamentally similar climatic reactions of pine and larch in other parts of Siberia have been observed previously (e.g., De Grandpré et al. 2011). On the other hand, these two species have differences in foliage habits (evergreen and deciduous) and in strategies for coping with moisture deficit. Isohydric Scots pine immediately regulates transpiration through stomata closure, but anisohydric Siberian larch maintains active transpiration, instead sacrificing needles and fine roots during severe droughts (Gower and Richards 1990; McDowell et al. 2008; Piper and Fajardo 2014; Khansaritoreh et al. 2018). These differences lead to species contrasts in radial growth rate during and after drought events (cf. pointer years observed in these chronologies in Zhirnova et al. 2021), and explain why inter-species correlations between chronologies drop much faster than intra-species correlations with an increase in the distance between sites.

Classification based on the inter-correlation of chronologies shows that, in general, the dynamics of radial growth of these conifers is determined primarily in the framework of geographic objects, i.e. a combination of short distances and similarities in habitat conditions (Fig. 1b). These objects are 1) the forest-steppe of the Kuznetsk Alatau foothills, 2) Minusinsky Bor, and 3) the low montane zone of Western Sayan. The only chronology opposing this geographic grouping is pine from site BID, which groups with pine chronologies of the Minusinsky Bor despite being located in the Kuznetsk Alatau. In the Western Sayan, regardless of the gradient of natural conditions from the forest-steppe to the sub-taiga, the chronologies of both species form one group.

The second implementation of cluster analysis, run on correlations of chronologies with monthly climate series, again classifies the network into three clusters, but these are more distinct than in the previous analysis, as indicated by the greater contrast of between-cluster and within-cluster distances (Fig. 1c; shaded areas on the map in Fig.1a). The three clusters are remarkably similar to those from the first cluster analysis. The single change is that one more pine chronology (BGD_PS) changes membership from the Kuznetsk Alatau cluster to the Minusinsky Bor cluster.

What is unique about the Minusinsky Bor cluster? This is the only cluster whose chronologies are significantly influenced by November precipitation (Fig. 1d). In the center of the valley, snowfall is extremely low (for quantitative spatial differences in monthly temperature and precipitation over a network of climatic stations across the KhMD, see Zhirnova et al. 2021). On average, only 10-20 cm of snow cover accumulates over the entire cold season, and much of that falls in November (data from station MIN). In winter, snow protects the root systems of trees from severe frosts. For evergreen conifers, photosynthesis in needles developed in past years is activated in the following spring when the soil thaws (Wu et al. 2013). Activation may even precede thawing, as studies have shown that photosynthesis in Scots pine is possible, although not very productive, in hours or days with a positive air temperature even when soil is frozen (Kolari et al. 2007; Yang et al. 2020). Similar observations have been made for other evergreen conifers (e.g., Tanja et al. 2003; Sevanto et al. 2006). The onset of active photosynthesis was recently reported to occur 2-4 weeks later in larch than in pine growing under similar conditions (forest-steppe in the vicinity of Krasnoyarsk, ~ 300 km north of the study area) by Urban et al. (2019). Consequently, when larch begins its primary growth and cambial activity, the small amount of snow is likely already fully melted. Pine therefore may have an advantage over larch in the KhMD in the ability to tap the meagre snowpack as a source of moisture.

We suggest this response to snow as the reason that pine and not larch at BID and BGD sites are classified in the Minusinsky Bor cluster, since climatic series from station Shira in the area shows only slightly more winter precipitation than at MIN (Zhirnova et al. 2021). The snow cover rapidly melts in spring and is available for use by pine, but not by larch because of its later growth start. Other studies also support a hypothesis that pine benefits from snowmelt in a wider range of environments than larch (Li et al. 2021; Zhang et al. 2019). In contrast to pine, larch at sites BID and BGD sites has a climatic response more similar to larch at other sites of the Kuznetsk Alatau than to pine at Minusinsky Bor. The Kuznetsky Alatau cluster is represented mostly by larch, and this is probably why this cluster has a strong dependence on water availability toward the end of the previous vegetative season: such a climatic response of larch tree-rings has previously been reported for the study area (Zhirnova et al. 2020). Larch annually completely renews its needles and therefore depends strongly on stored assimilates when growth starts (Gower and Richards 1990; Piper and Fajardo 2014).

The Western Sayan region, the last of our clusters, is characterized by more abundant snowfall than the other regions (comparing CHER and other stations' data) and by a heterogeneous landscape that hinders snowmelt in shaded areas. These conditions apparently allow both species in this zone to use the precipitation of the second half of winter as a source of moisture. The weakest correlation with precipitation, observed at the SHB site, is probably due to the lesser degree of moisture deficit in the sub-taiga zone due to the gradient of annual precipitation of ca. 100-200 mm per 100 m of elevation in the Western Sayan Mountains (Polikarpov and Nazimova 1963). More information on station-to-station climate variability in the Western Sayan Mountains can be found in Babushkina et al. (2018). Despite its weak correlation with precipitation, chronology SHB still correlates substantially (0.43 to 0.44) with other pine chronologies in the Western Sayan cluster.

Conclusion

Scots pine and Siberian larch share a common semi-arid boundary in the forest steppe of southern Siberia. For the most part, their growth and climatic signal there depends primarily on climate-landscape patterns of natural zones and habitats. However, ecophysiological and phenological differences between these species are also important to the spatial classification and climate response of drought-sensitive tree-ring chronologies in the KhMD, a relatively hot and dry territory whose climate may become increasingly representative in Siberia under climate change. We suggest that the snow regime may have an especially large influence on the distributions of these two competing tree species. While warming air temperature can be expected to influence the snow regime, no significant temporal shifts or trends have been hitherto found in the total winter precipitation across the region, but only spatial differences (see Zhirnova et al. 2021). Heterogeneity of growth response to climate change may lead to significant change in the species composition of vulnerable forest-steppe ecotone ecosystems at all levels, starting with forest-forming trees.

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Table 1. Tree-ring sampling sites and chronologies

Site		Coordinates				Chronologies		
Name	Code	N	E	h, m asl	Tree species*	No. of cores	Cover period (years)	*r-bar*
Zelyony Shum	ZSH	53.65	91.60	300	PS	144	1881-2017	0.31
Malaya Minusa	MMIN	53.75	91.77	300	PS	40	1847-2013	0.41
Taraska	TAR	53.75	91.77	350	PS	34	1914-2013	0.49
Malaya Nichka	MNIC	53.62	92.05	380	PS	29	1872-2013	0.43
Bograd	BGD	54.20	90.83	600	PS	80	1847-2018	0.42
					LS	44	1845-2019	0.47
Bidja	BID	54.00	91.02	660	PS	16	1874-2018	0.56
					LS	68	1704-2019	0.45
Kamyzyak	KAM	53.92	90.60	730	LS	61	1710-2019	0.44
Kazanovka	KAZ	53.22	90.08	685	PS	67	1767-2013	0.53
					LS	20	1835-2013	0.47
Kaly	KALY	53.05	91.28	520	PS	13	1947-2012	0.33
					LS	13	1946-2012	0.51
Mayna	MAY	52.97	91.35	400	PS	27	1947-2017	0.46
Shushensky Bor	SHB	52.83	91.45	520	PS	31	1914-2015	0.30

* PS – *Pinus sylvestris* L., LS – *Larix sibirica* Ledeb.

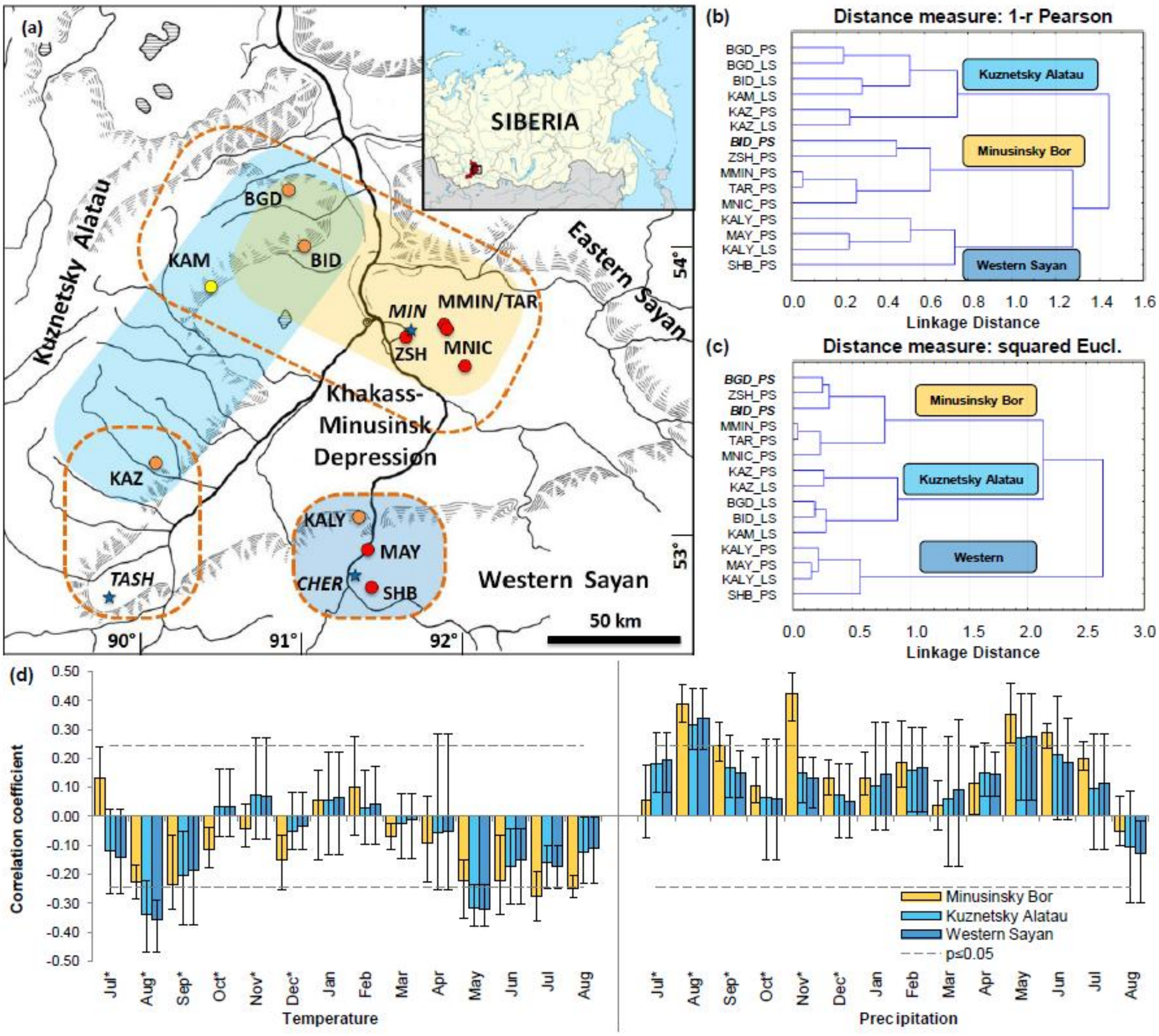

Fig. 1 Spatial classification of tree-ring chronologies. **(a)** Map of the study area, with climate stations (asterisks) and tree-ring sites (red circles, *Pinus sylvestris* L.; yellow circles, *Larix sibirica* Ledeb.; orange circles, both sp.). Dashed boundaries mark climate stations and groups of tree-ring sites for correlation analysis of chronologies with monthly climate variables (e.g., station CHER climate data were correlated with chronologies at sites KALY, MAY, CHER, and SHB); shaded areas delineate geographic zones identified by clustering of tree-ring chronologies based on their climatic correlations. **(b)** Dendrogram from cluster analysis on between-chronology correlations, 1936-2014. **(c)** Dendrogram from cluster analysis on dendroclimatic correlations (r), i.e., on correlations of chronologies with monthly temperature and precipitation (previous July to current August). Correlation period varies according to overlap of chronology and climate series. **(d)** Dendroclimatic correlations used for second application of cluster analysis. Bars show mean value and whiskers show range of r within clusters. Horizontal dashed lines mark the threshold ($|r|>0.246$) of r significance at $p<0.05$ for even the shortest correlation period