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Variability of climate–growth relationships along an elevation gradient in the Changbai Mountain, northeastern China

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Abstract In order to explore climate–growth relationships at different elevations, tree-ring width chronologies of larch (*Larix olgensis*) were developed from three sampling sites on the northern slope of the Changbai Mountain, northeastern China. There were no consistent trends in statistical characteristics of the tree-ring chronologies along the elevation gradient, since trees in the forest interior had a complacent growth pattern. Monthly mean temperature and monthly total precipitation were used for the analysis. Correlation analysis indicated that temperatures in winter had negative correlations with tree growth (previous November, December and current March for the low-, mid- and high-elevation sites, respectively). The correlations between tree growth and June temperature varied from weakly negative at low elevations to significantly positive at high elevations. Precipitation in June of the growth year had negative relationship with the high-elevation chronology. However, high precipitation was associated with low temperature in early growing season, further supporting that temperature is a growth-limiting factor at high elevations. Our results suggest that along the elevation gradient, *L. olgensis* may respond in different ways to local climate change.

Keywords *Larix olgensis* · Tree-ring · Elevation · Dendroclimatology

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Introduction

The tree-ring width sequences are indicative of the environmental conditions affecting tree growth (Frrits 1976). Trees growing at the margins of their distributional range are considered to be most sensitive to environmental factors (Kullman 1993). Frrits (1976) had deduced that trees were more sensitive to temperature close to the treeline than at lower altitudes, whereas there is often a positive relationship between growth and precipitation at the low altitude (Splechtna et al. 2000; Peterson and Peterson 2001; Dittmar et al. 2003). The importance of altitudinal was emphasized (Fritts 1965). For tree species distributed across wide elevation gradients and playing vital roles in local ecosystems, the altitudinal variation of growth conditions may be of great importance for sustainable forest management.

In this study, we used dendroecological methods to quantify the effects of climatic variability on *Larix olgensis* growth at the annual timescales along an elevational gradient on the northern slope of the Changbai Mountain. *Larix olgensis* was chosen as the target species for this study because it is a common coniferous species in the Changbai Mountain and is economically important in the northeastern China (Institute of Environment Protection of Jilin 1988). *Larix olgensis* is distributed across a wide elevational range spanning from 500 to 1,950 m a.s.l. on

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the northern slope of the Changbai Mountain (Wang et al. 1980). Dendroclimatic studies of the growth-climate response of *Larix olgensis* and reconstruction of past temperatures have been carried out in the Changbai Mountain region (Wu and Shao 1996; Shao and Wu 1997; Yu et al. 2005; Zhu et al. 2009). For example, Wu and Shao (1996) reported possible impact of air temperature increase on tree volume growth at high elevations. Shao and Wu (1997) carried out a dendrochronological analysis of *Larix olgensis* at a high-elevation site and reconstructed regional temperatures. Yu et al. (2005) compared tree growth-climate responses of *Larix olgensis* between the upper treeline and interior forest. While the former was significantly correlated to June temperature, the latter had more complex climate–tree growth relationships. *Larix olgensis* growing at high-elevation sites has been found to be relatively sensitive to climate (Wu and Shao 1996; Yu et al. 2005). However, little information was available on the growth of *Larix olgensis* at low elevations and the growth information derived from high elevations may not be applicable at low elevations. It is of interest to know what factors limit the growth of this species at lower elevation sites and whether its growth responses change with elevation. As there were little related studies in the Changbai Mountain, we hypothesized that climate–growth relationships vary along elevation gradients. Thus, samples were collected at different elevations to examine the dependence of climate–growth relationships on altitude in this region.

The objectives of this study were (1) to construct three tree-ring width chronologies of *Larix olgensis* using samples from sites of different elevations; (2) to investigate the climate–tree growth relationships at these sites. This study may contribute to the existing body of knowledge on regional dendroclimatology.

Materials and methods

Study area and climate

The sampling was conducted on the northern slope of the Changbai Mountain in the Changbaishan Nature Reserve in the east Jilin Province, northeastern China (Fig. 1). The Changbai Mountain is composed of granite and metamorphosed rocks of the early stage of Cenozoic and massive basalts of Cenozoic and modern times (Zhou et al. 1984). The soil near the base of the Changbai Mountain is approximately 50 cm deep and classified as the mountain brown forest soil (ECJF 1988). Soil depth becomes shallower as elevation increases, and at the top of the study area the soil is approximately 20–30 cm deep and classified as the mountain brown coniferous forest soil (ECJF 1988). The varied topography and distinct precipitation gradient strongly influence the local variation in vegetation composition. Forest vegetation varies from coniferous and broad leaf mixed forests dominating the lower elevations (500–1,100 m a.s.l.) to subalpine coniferous forest at the higher elevations (1,100–1,800 m a.s.l.) (Editorial Committee for Vegetation of China 1980).

The climate of the Changbai Mountain region is characterized by a cold and long winter period and a short and cool summer period. The annual mean temperature ranges from −7 to 3°C, and the annual precipitation ranges from 700 to 1,400 mm during 1959–1988 (Fig. 2). The closest meteorological stations to the sampling sites are Erdao (591.4 m a.s.l.) and Tianchi (2,623 m a.s.l.) (Fig. 1). The data of the two stations were checked using the Mann–Kendall method (Kendall and Gibbons 1990) and no abrupt level on variance changes were found. The Erdao meteorological station was moved from its first location in January 2005, but the data were continuous and homogeneous. The climatic data at Tianchi were rather limited as observations during winter were terminated in 1989. Based on the monthly data for the 1959–1988 periods, the correlations of climatic data between the two stations were significant ($p < 0.05$). Thus, we only used the long-term climatic data recorded at Erdao in this study.

Tree-ring sampling and chronology development

The sampling was carried out in July of 2008. Three sampling sites were chosen to represent the elevation range of *Larix olgensis*: the low-elevation site (LTD at 794 m a.s.l.), the mid-elevation site (LY2 at 1,258 m a.s.l.), and the high-elevation site (CB1 at 1,800 m a.s.l.), which was sampled in 2002 in an earlier investigation (Zhu 2006) (Table 1). The low-elevation site was above the lower range margin of the species' distribution, while the high-elevation site was approximately 150 m below the upper treeline. The vertical distance between the upper and lower sites was about 1,000 m. All sites are on the same slope and subject to similar weather patterns. At each site, 20–30 of the largest and presumably oldest trees with no visible damage to crowns or stems were selected for increment core sampling. Two cores were extracted from each tree about 1.3 m above the ground level. A total of 170 cores were collected from 82 living *Larix olgensis* trees (Table 1).

All cores were air dried, glued to wooden mounts in the laboratory, and then polished by hand with progressively finer sandpaper. Ring patterns were visually cross-dated (Stokes and Smiley 1968) using a binocular microscope. Ring widths were measured to the nearest 0.01 mm using a moving-stage measuring device LINTAB (Frank Rinn, Heidelberg, Germany) to produce a ring-width time series for each tree. Following measurement, cross-dating accuracy was verified using the program COFECHA (Holmes

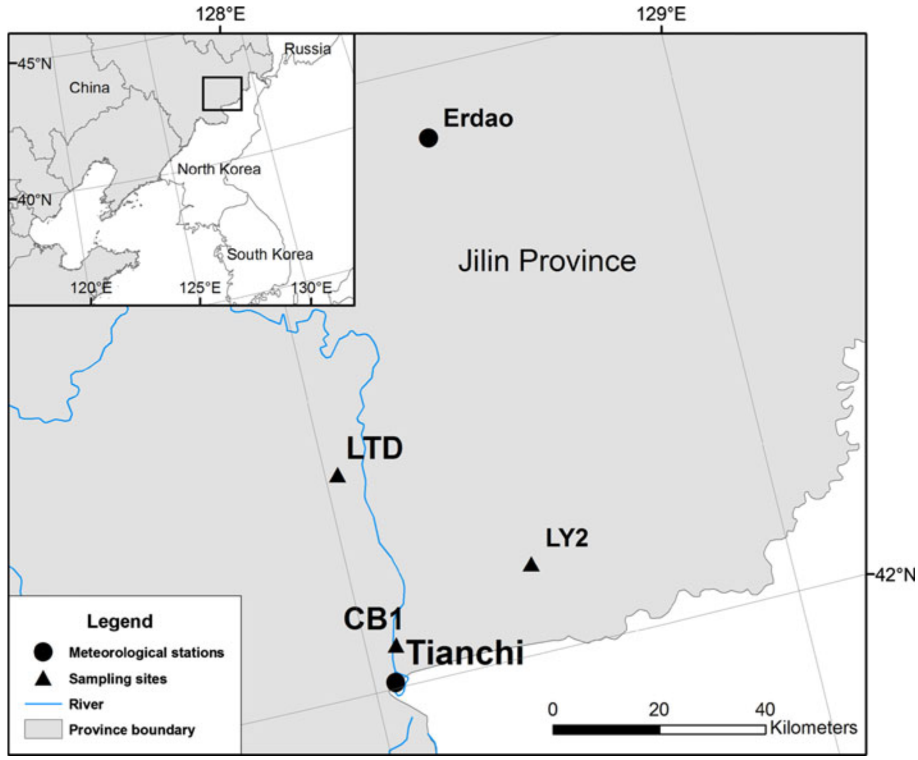

Fig. 1 Locations of sampling sites and meteorological stations in the Changbai Mountain of Jilin Province, northeastern China

1983) and sections of any cores that were poorly matched with the COFECHA master series for each site were identified and excluded from the analysis.

Larix olgensis growth chronologies were developed from the cross-dated ring-width series using the program ARSTAN (Cook and Holmes 1996). The cross-dated measurement series were detrended by fitting a cubic spline with 67% of the series length to the series to remove the biological growth trends of each series that was associated with age. The chronology was then computed as a biweight robust mean of the detrended and standardized individual series (Cook et al. 1990). The chronologies were also prewhitened by performing autoregressive modeling on the detrended ring-width measurement series to produce a residual chronology. In general, the sample size declined in the early portion of a tree-ring chronology; therefore, we used the expressed population signal [EPS] (Wigley et al. 1984) with a threshold value of 0.85 to evaluate the useful time span of the final chronologies, which gives the minimum number of cores that can be used to produce a reliable chronology.

Climate-tree growth relationships

Correlation analysis and partial correlation analysis were performed using the SPSS software (http://www.spss.com/spss/). Pearson's correlation coefficients were calculated between the chronologies and climatic variables to assess which variables are significantly related to tree growth ($p < 0.05$). Partial correlation analysis between the chronologies and climatic variables was also performed to avoid the effect of intercorrelation among climatic variables. In addition, Single-year analysis (Kienast et al. 1987) was used to examine the climate–growth relationships. Climatic variables used in this study included monthly mean temperature and monthly total precipitation. The analysis examined a sequence of 15 months starting from July of prior year to September of the growing season, as the climatic conditions of the prior year may have effects on tree growth of the current year (Frrits 1976). The study period was set from 1958 to 2002, in order to make the climate–growth relations comparable among all the sites.

Results

Chronology characteristics at different elevations

Figure 3 shows the three final residual chronologies with EPS > 0.85 from low to high elevations. Descriptive statistics were presented in Table 1. Mean sensitivity (MS) and standard deviation (SD) described interannual variability in ring widths as a proportion of the local mean ring width. Both values were highest at the high-elevation site and lowest at the mid-elevation site (Table 1). Low values of MS, SD, and Signal-to-noise ratio (SNR) suggested that trees in the mid elevation site had a complacent growth pattern. There were no consistent trends in the basic

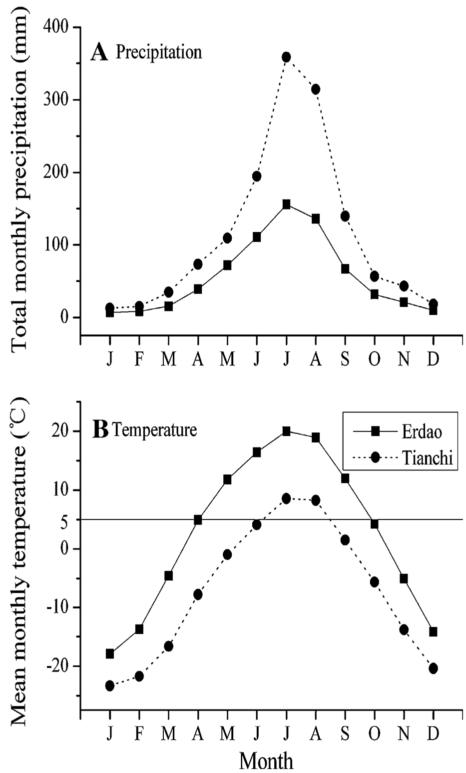

Fig. 2 Mean monthly temperature (°C) and total monthly precipitation (mm) for the two meteorological stations in the Changbai Mountain of Jilin Province, northeastern China. B. The *long line* is a 5°C for monthly mean temperature line, which indicates a growing season of plants

Table 1 Site information, chronology statistics and common interval (1931–2000) statistics of the three sampling sites from different elevations on northern slope of the Changbai Mountain

Site code	LTD	LY2	CB1
Elevation (m)	794	1,258	1,800
Latitude (N)	42°22′	42°08′	42°04′
Longitude (E)	128°01′	128°28′	128°04′
No. radii/trees	62/29	49/24	59/29
Time span	1792–2007	1791–2007	1685–2002
EPS $\geq$ 0.85 starting year	1824	1809	1745
Mean sensitivity (MS)	0.229	0.168	0.284
Standard deviation (SD)	0.185	0.154	0.233
First-order autocorrelation (AC)	0.072	0.034	0.078
Mean correlations			
Among all radii (R_1)	0.478	0.346	0.433
Between trees (R_2)	0.474	0.341	0.429
Within trees (R_3)	0.697	0.532	0.623
Signal-to-noise ratio (SNR)	46.770	21.162	42.783
Express population signal (EPS)	0.979	0.955	0.977
Variance explained by the first principal component (PC1%)	49.7	37.1	45.1

statistics, such as MS, SD, and SNR along the elevation gradients (Table 1). The correlation coefficients among all radii (R_1), between trees (R_2) and within trees (R_3) were highest at the low elevation and lowest at the mid elevation (Table 1), with higher values indicating greater similarities in the annual growth patterns among the sampled trees and better representation of the overall stand growth by the mean growth chronologies. Generally, all the three chronologies of the current study had high values of SNR, EPS, and PC1 (Table 1).

The three resulted tree-ring width chronologies displayed years with wide and narrow rings (1958–2002 periods). The widest rings were found in 1989/1990, 1966/1967, and 1965 at LTD, LY2, and CB1, respectively. The narrowest rings occurred in 1975/1976 at LTD, 1999/2000 at LY2, and 1969 at CB1.

Tree growth patterns in relation to elevation changes

To assess the similarity among chronologies and any potential differences due to the changes in elevation, the relationships among the chronologies were analyzed using correlation analysis. There was a significant positive correlation between the low- and mid-elevation chronologies, while the correlations of the high-elevation chronology to those of mid- and low-elevation were not statistically significant (Table 2). Apparently, there were different growth patterns along the elevation gradient, which may reflect the influences of distinct climatic factors on tree growth at different elevations.

Climate–growth correlations

Figure 4 displays the correlation coefficients of tree-ring widths with the climatic variables at the three sites. *Larix olgensis* growths at the low- and mid-elevation sites were negatively correlated with the prior November and December temperatures, respectively ($p < 0.05$; Fig. 4b). The current September precipitation showed a negative correlation with the tree-ring width index of the mid-elevation chronology ($p < 0.05$; Fig. 4a). On the other hand, the tree-ring width index at the high-elevation site was negatively correlated with March temperature and June precipitation ($p < 0.05$; Fig. 4), but it was positively correlated with the current June temperature at this site ($p < 0.05$; Fig. 4b). Partial correlation analysis suggested the relationship between the tree-ring width index and June precipitation was rather weak when the effect of temperature in June was controlled.

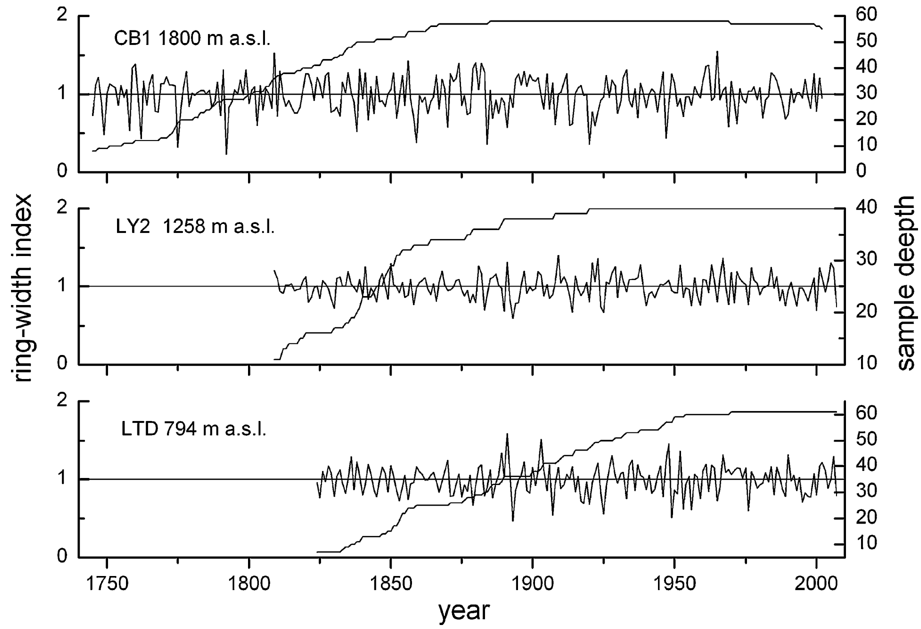

Fig. 3 The residual chronologies of *Larix olgensis* and the number of samples from different elevations along the slope

Table 2 Coefficients of residual chronologies between three sampling sites (1850–2000 year)

	LTD	LY2	CB1
LTD	1		
LY2	0.533**	1	
CB1	−0.141	0.122	1

** Significant level of $p < 0.01$

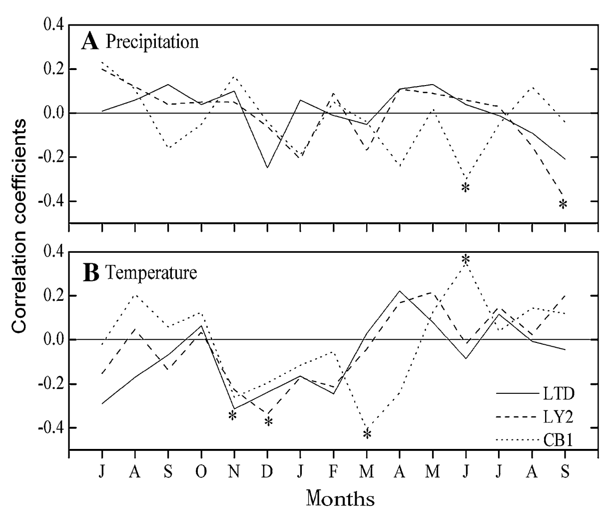

Fig. 4 Results of the correlation analysis for the relationships between the residual chronologies of *Larix olgensis* and monthly climatic data (precipitation and mean temperature). Significant relationships ($p < 0.05$) are indicated by *asterisks*

Discussion

There were two important patterns regarding the relationships of tree growth with temperature. First, negative correlations with winter temperatures were common at all three sites. High-temperature limitations in early winter (November–December) had large effects on low and mid elevations. This result perhaps reflected uniformity of tree growth patterns. The growth of many tree species was affected not only by the climatic conditions of the current year but also by those of the previous year (Rolland 1993; Bräuning 1999; Savva et al. 2006). This view was confirmed in our study. Although our results were different from some previous studies that showed positive correlations of tree growth with temperature in the prior winter (Peterson and Peterson 1994; Pederson et al. 2004; Fan et al. 2009; Liang et al. 2010), Takahashi et al. (2005) showed that *Betula ermanii* was negatively correlated with December and January temperatures at the treeline in Japan. As for the negative associations of tree growth with the prior winter temperatures, it is possible that high temperatures could enhance respiration rates, which decreased the storage of the carbohydrate production (Pilcher and Gray 1982).

Our results of tree growth-climate relationships at the mid-elevation site were different from those in a previous study (Yu et al. 2005). Yu et al. (2005) reported that the tree-ring widths had negative correlations with the prior June, September, and November temperatures and positive correlations with the current year spring temperatures. The discrepancies between the two studies were obvious; however, the underlying reasons that caused these discrepancies are unclear and future research is needed to explain the differences.

The growth of *Larix olgensis* at the high-elevation site was limited by high late winter (March) temperature. Furthermore, March (minimum and maximum temperature) and April (minimum temperature) had negative

effects on tree growth (results not shown). This result was similar to what has been previously reported for the species by other researchers (Wu and Shao 1996). Shao and Wu (1997) showed that warm March–April was unfavorable for growth. At the high elevation, winters were cold and long, and the March mean air temperatures was normally below −10°C (Fig. 2). Therefore, a warm March would not activate the cambium earlier but consume the photosynthetic reserves of the previous year.

Second, tree growth was correlated with June temperature ranging from weakly negative at the low-elevation site to significantly positive at the high-elevation site. Yu et al. (2005) also found a statistically significant correlation between tree growth and June temperature at the upper treeline (approximately 1,950 m a.s.l.). Many researchers have reported that tree growth was limited by low summer temperature at high altitudes and high latitudes (Gostev et al. 1996; Gervais and MacDonald 2000; Barber et al. 2004). Camarero et al. (1998) showed that high temperatures in early summer were effective for tree growth by prolonging the duration of growing season. Additionally, high temperature in June would enhance leaf area and the photosynthetic rate. Compared with high-elevation site, trees at low elevations may decrease growth in response to water stress because high temperature increased summer evaporation demand.

Three inferences can be made regarding the correlations of tree growths with precipitation. First, at the low-elevation site, the soil moisture condition was good through most of the years (Wang and Tao 1998), and any significant correlation between tree growth and precipitation was absent. Second, considering that tree may stop cell division in September, the correlation with precipitation seemed not to have a physiological meaning at the mid-elevation site. Third, at the high-elevation site, the correlation analysis showed that the tree-ring widths of *Larix olgensis* had a negative correlation with June precipitation. A similar result of high precipitation in June and July corresponding to a narrow ring has been reported for *Larix* in the French Maritime Alps (Serre 1978). However, there was no significant partial correlation between June precipitation and tree growth when June temperature was controlled; suggesting that tree growth was further controlled by temperature.

Extreme weather conditions may affect tree growth in the study area, whose impacts can be illustrated by the single-year analysis. At the low-elevation site remarkable positive deviation was obvious in 1989/1990, which could be related to the below-normal November temperature in 1989. After the cold weather in December 1966, tree growth in the next year showed a significant increase at LY2. Most trees at the high-elevation site seemed to benefit from the cold weather in March 1965 since wide rings were detected for that year. Growth reduction during the years 1975/1976, 1999/2000, and 1969 at all three sites could be explained again by short-term weather impacts: exceptional warm winter plus cool and wet June. Thus, the relationships of climate–growth were well proved by single-year analyses.

Conclusions

The analysis of growth–climate relationships in the Changbai Mountain showed that temperatures, not precipitation, were the most important limiting factors on tree growth. High temperatures in prior winter limited tree growth throughout the elevation range, while high temperature in early summer was effective for tree growth at high-elevation site. June precipitation affected tree growth at the high-elevation site, and this influence was not independent of temperature because of the inverse relationships of precipitation with temperature. Therefore, tree growth at the low-elevation sites would be constrained by increased temperatures, whereas tree growth at the high-elevation sites would have both positive and negative response to climate change.

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