Climate–growth relationships of Schrenk spruce (*Picea schrenkiana*) along an altitudinal gradient in the western Tianshan Mountains, northwest China

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Key message The elevation-dependent tree growth patterns and climate–growth relationships were inferred from five tree-ring chronologies of *Picea schrenkiana* along an altitudinal gradient in the western Tianshan Mountains, northwest China.

Abstract

Schrenk spruce (*Picea schrenkiana*) is a crucial tree species in the western Tianshan Mountains of northwest China and plays a vital role in local ecosystems; it is of particular importance to assess the growth response of this species to climate in the context of global climate change. In this study, five tree-ring width chronologies of *P. schrenkiana* were developed along an altitudinal gradient ranging from 1499 to 2820 m a.s.l. to investigate the radial growth variations and climate–growth relationships at different elevations. The statistical characteristics of tree-ring chronologies, combined with results of correlation matrix and rotated principal component analysis, suggested that elevation played a crucial role in determining tree growth patterns in the study area. Correlation analyses of tree-ring chronologies with climate variables indicated that climate–growth relationships changed with increasing altitude. Tree growth at the low-elevation sites was primarily limited by moisture availability. With increasing altitude, the importance of precipitation decreased, tree growth at the high-elevation sites was mainly controlled by lower temperature. These results will help understand the growth response of *P. schrenkiana* to future climate change, and provide critical information for climate reconstructions using this tree species in the study area.

Keywords Tianshan Mountains; Tree ring; *Picea schrenkiana*; Altitudinal gradient; Climate–growth relationship

Introduction

Tree rings are an exceptionally valuable source to study climate variations and dynamics of forest ecosystem (Fritts 1976; Gou et al. 2012). Dendrochronological studies of tree growth response to climate factors and subsequent reconstructions of past climate history have been carried out in many regions around the world (e.g., Büntgen et al. 2005; Shao et al. 2005; D'Arrigo et al. 2009; Chen et al. 2015). In the context of global climate change, tree growth and its response to climate variability have attracted much attention (e.g., Savva et al. 2006; Sang et al. 2007; Fang et al. 2009a; Qi et al. 2015; Wu et al. 2015). Climate change may lead to changes in tree growth and forest productivity. A detailed understanding of tree growth response to climate factors is not only an ecological issue, but also an important component of global change research (Liang et al. 2006).

In dendroclimatological studies, it is generally observed that relationships between tree growth and climate factors are complicated by differences in tree species and site conditions (Liang et al. 2006; Büntgen et al. 2007; Leal et al. 2007; Fang et al. 2009a), and the impacts of environmental factors on tree growth may vary along altitudinal, latitudinal, and longitudinal gradients (Buckley et al. 1997; Sang et al. 2007; Fan et al. 2009). In mountainous areas, tree growth conditions differ with altitude, and as a result the climate–growth relationships may vary with altitude (Splechtna et al. 2000; Savva et al. 2006; Fan et al. 2009). For example, early studies reported that tree radial growth at high-elevation timberline sites is typically limited by temperature, while that at low-elevation sites is mainly controlled by precipitation

(Fritts et al. 1965; LaMarche 1974). A large quantity of research in many regions has generally supported this principle of climate–growth relationship (Di Filippo et al. 2007; Leal et al. 2007; Fan et al. 2009). However, many other studies have shown different results challenging this general principle, with uniform growth patterns observed at both the upper and the lower forest limits in different regions (Esper et al. 2007; Gao et al. 2013; He et al. 2013; Yang et al. 2013). For example, in the areas where precipitation is sufficient for tree growth, temperature may be the determining factor in controlling radial growth along altitudinal gradients from low- to high-elevations (Liang et al. 2010). Thus, variations in tree growth along altitudinal gradients may also be influenced by mean climate conditions in a region. The general effects of altitude on climate–growth relationships should be carefully evaluated and more work should be undertaken in various mountainous regions.

The Tianshan Mountains are considered as an area sensitive to global climate change (Sang et al. 2007). There are a growing number of dendrochronological studies being conducted in this region (e.g., Yuan and Li 1999; Yuan et al. 2000; Yuan et al. 2001; Zhu et al. 2004; Wang et al. 2005; Li et al. 2006; Chen et al. 2010; Chen et al. 2013; Wu et al. 2013b; Liu et al. 2015; Wu et al. 2015). The Schrenk spruce (*Picea schrenkiana*) forests are distributed across a wide altitudinal range in the Tianshan Mountains, and play a vital role in local ecosystems. The dendrochronological features of this species across altitudinal gradients are important for understanding and protecting forests and local ecosystems (Wang et al. 2005; Sang et al. 2007). Several studies have investigated tree growth variations of *P. schrenkiana* in response to climate at different elevations in the Tianshan Mountains (Zhu et al. 2004; Wang et al. 2005; Guo et al. 2007; Wu et al. 2015). The results showed that tree growth response to climate is complicated by differences in topography and climate, and there is a need to investigate climate–growth relationships in different areas with varying climates. The Yili valley of the western Tianshan Mountains in northwest China has unique topography and natural conditions. How changing elevation influences tree growth in this area is of considerable interest.

Based on five tree-ring width chronologies of *P. schrenkiana* across an altitudinal gradient ranging from 1499 to 2820 m a.s.l. in the western Tianshan Mountains of northwest China, the present study will investigate the effects of altitude on radial growth variations and climate–growth relationships. The main objectives are: (1) to detect and compare the tree growth patterns of *P. schrenkiana* along an altitudinal gradient; and (2) to evaluate the climate–growth relationships accounting for such growth patterns.

Materials and methods

Study area

Our study area is located in the Yili valley (42°14′–44°50′N, 80°09′–84°56′E) of the western Tianshan Mountains, northwest China (Fig. 1). The valley is an intermontane basin with the opening toward the west and surrounded by mountains on all the other sides. Due to this special topography, the westerly airflow enters directly into the valley and contributes to the formation of orographic rain on the windward slope, while cold air flows from Siberia are blocked by the northern mountains (Wu et al. 2013a). This area features temperate semiarid continental climate. Instrumental records from four meteorological stations (Fig. 1) show that the annual total precipitation is about 417 mm and the annual mean temperature is about 6.4 ℃ during the period 1960–2004. About 75% of the annual precipitation falls during the warm season (April–September), and June is the wettest month with precipitation of 66 mm. July is the warmest month with mean temperature of 19.0 ℃ and January is the coldest month with mean temperature of -9.6 ℃.

In the study area, *P. schrenkiana* is the dominant species, and is distributed across a wide altitudinal range extending from 1500 to 2800 m a.s.l. (Zhu et al. 2004). The species is evergreen and shade-tolerant, and mainly grows on the relatively wet and shady slopes. The dominant soil type is mountain gray-brown forest soil. Tree-ring samples were collected from five *P. schrenkiana* stands along an altitudinal gradient ranging from 1499 to 2820 m a.s.l. on the northern slope of the western Tianshan Mountains (Fig. 1, Table 1), covering the entire altitudinal range of the tree species in this region. All the five sampling sites had approximately similar canopy density (40–60%), soil depth (60–90cm), slope (30–35°) and exposure (north facing). For each site, at least 20 dominant trees were selected and two cores per tree were extracted at breast height using 5-mm increment borers. In total, 230 cores from 118 trees were collected at the five sites (Table 1).

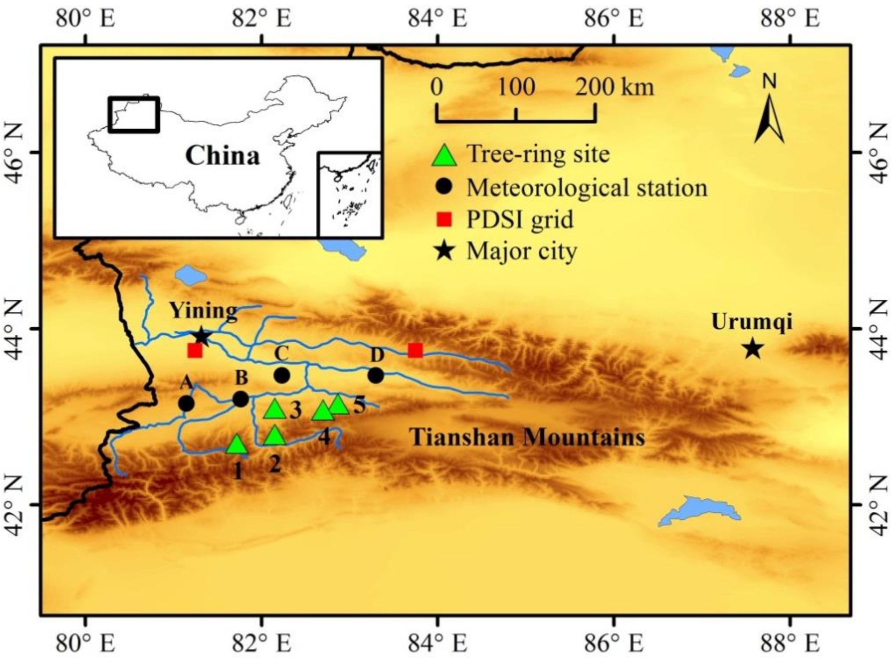

Fig. 1 Locations of the tree-ring sampling sites (the number *1*–*5* represents KEN, WUY, JAL, QIA, and KUE, respectively) and the nearby meteorological stations (the capital letter *A*–*D* represents Zhaosu, Tekesi, Gongliu, and Xinyuan, respectively)

Table 1 Descriptions of the five sampling sites in the western Tianshan Mountains

Site code	Latitude (N)	Longitude (E)	Elevation (m a.s.l.)	Cores/trees	Time span
KEN	42°47′36.8″	81°43′04.9″	2820	41/21	1686–2004
WUY	42°53′11.9″	82°07′34.5″	2763	44/23	1690–2004
JAL	43°04′29.1″	82°08′49.9″	2308	57/29	1605–2004
QIA	43°05′16.2″	82°41′21.9″	1710	42/22	1721–2004
KUE	43°09′16.1″	82°52′29.1″	1499	46/23	1634–2004

Climate data

Climate data (i.e., monthly mean, maximum and minimum temperature, and monthly total precipitation) were obtained from four nearby meteorological stations, including Zhaosu, Tekesi, Gongliu, and Xinyuan (Fig. 1, Table 2). Due to its higher altitude, Zhaosu is colder and wetter than the others, while Gongliu and Xinyuan are warmer than Zhaosu and Tekesi for their relatively lower altitudes (Table 2). Although the absolute climates differ at the four stations, they showed synchronous variations over the common period 1960–2004 (Fig. 2). As shown in Table 3, the correlation coefficients of the annual mean temperature at the four stations range from 0.913 to 0.956, while those of the annual total precipitation range from 0.658 to 0.827 during the period 1960–2004 (p<0.001). Considering that meteorological stations along the mountain slope are not available, especially there is no high-elevation meteorological station in this area, we averaged the climate data from the above four stations to highlight the regional climate features (Fig. 3). The correlation coefficients of the annual mean temperature (annual total precipitation) between the regional mean series and the individual Zhaosu, Tekesi, Gongliu and Xinyuan stations over the period 1960–2004 are 0.971 (0.861), 0.980 (0.902), 0.971 (0.901), and 0.976 (0.916), respectively (Table 3), which shows that the regional mean series can well depict the climate conditions in our study region, and was therefore used to test the climate–growth relationships of *P. schrenkiana* at different elevations.

In addition, a gridded (2.5°×2.5°) version of the Palmer Drought Severity Index (PDSI; Dai et al. 2004) was also used to investigate the relationship between tree growth and regional moisture availability. The PDSI data from the two closest grids to the sampling sites (Fig. 1, Table 2), with monthly correlation coefficients from 0.675 to 0.882 during the period 1960–2004 (p<0.001), were averaged to represent the regional drought variations.

Table 2 Information about the four meteorological stations and the PDSI grids used for climate–growth analysis

Station	Latitude (N)	Longitude (E)	Elevation (m a.s.l.)	Annual mean [a] temperature (℃)	Annual total [a] precipitation (mm)	Time span
Zhaosu	43°09′	81°08′	1854.6	3.24	504.4	1954–2004
Tekesi	43°11′	81°46′	1210.9	5.77	393.0	1960–2004

Gongliu	43°28′	82°14′	775.6	7.83	275.5	1960–2004
Xinyuan	43°27′	83°18′	929.1	8.78	495.7	1956–2004
PDSI	43°45′	81°15′				1960–2004
PDSI	43°45′	83°45′				1960–2004

[a] Calculated over the common period 1960–2004

Table 3 Correlation matrix of the annual total precipitation (left-down part) and annual mean temperature (right-upper part) at the four meteorological stations as well as corresponding mean series over the period 1960–2004

	Zhaosu	Tekesi	Gongliu	Xinyuan	Mean
Zhaosu		0.956	0.913	0.931	0.971
Tekesi	0.779		0.936	0.936	0.980
Gongliu	0.665	0.763		0.932	0.971
Xinyuan	0.658	0.731	0.827		0.976
Mean	0.861	0.902	0.901	0.916	

All correlations are significant at the 0.01 level (2-tailed)

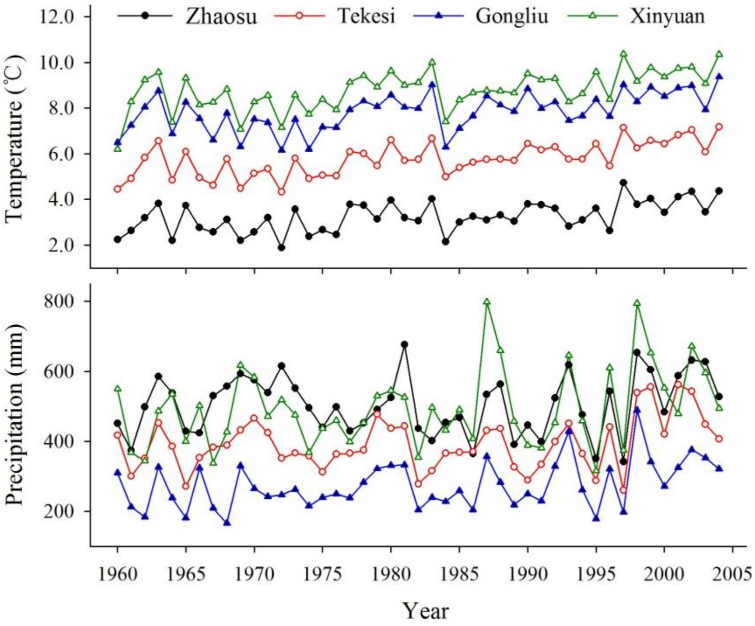

Fig. 2 Annual temperature and precipitation recorded at the Zhaosu, Tekesi, Gongliu and Xinyuan stations over the common period 1960–2004

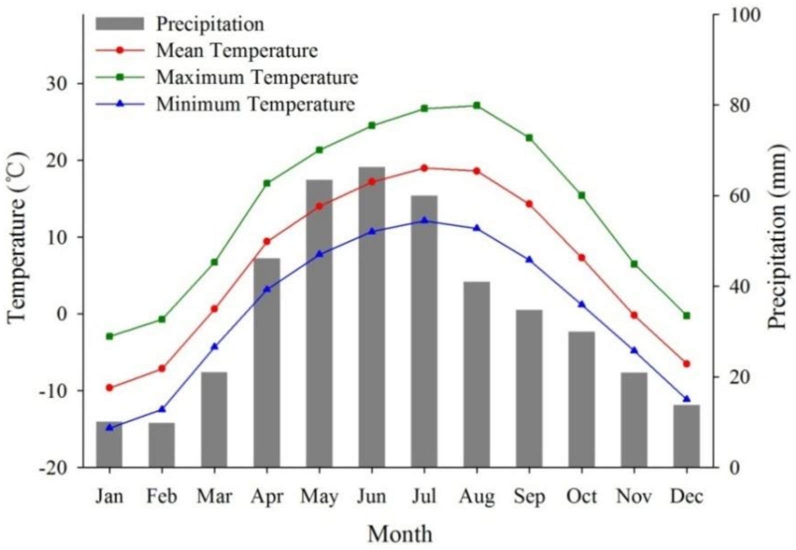

Fig. 3 Regional mean monthly temperature and monthly precipitation based on available records (1960–2004) from the four meteorological stations

Tree-ring data

In the laboratory, the tree-ring cores were processed following standard dendrochronological techniques (Stokes and Smiley 1996). After air drying, mounting and sanding, all the cores were carefully cross-dated by visual comparison, and ring widths were subsequently measured to 0.001 mm precision using a Velmex measuring system. The cross-dating and measurement were then checked by the COFECHA program for quality control (Holmes 1983).

Tree-ring width chronologies were developed from the cross-dated series using the ARSTAN program (Cook 1985) by removing biological growth trends while preserving variations that are likely related to climate. About 87% (200 series) of all the raw ring-width series were conservatively detrended with negative exponential curves or linear regression curves of negative or horizontal slope. The remaining series (30 series) that could not be fitted well by conservative curves were detrended by a cubic smoothing spline with 50% frequency-response cutoff at 67% of the series length. The tree-ring indices were calculated as the ratios between the original ring widths and the fitted curves. Autoregressive modeling was also applied to remove much of the autoregressive properties in each series, and the bi-weight robust mean method was used to calculate the chronology for each site (Cook 1985). To reduce the potential influence of changing sample size, the chronology variance was stabilized with the Briffa rbar-weighted method (Osborn et al. 1997). The standard and residual chronologies were developed for each site. To emphasize inter-annual high-frequency variations, the ‘‘pre-whitened’’ residual chronologies (Fig. 4) were used for further analysis where biologically related persistence has been removed (Cook 1985). The subsample signal strength (SSS) with a threshold value of 0.85 was used to identify the most reliable period of each residual chronology (Wigley et al. 1984).

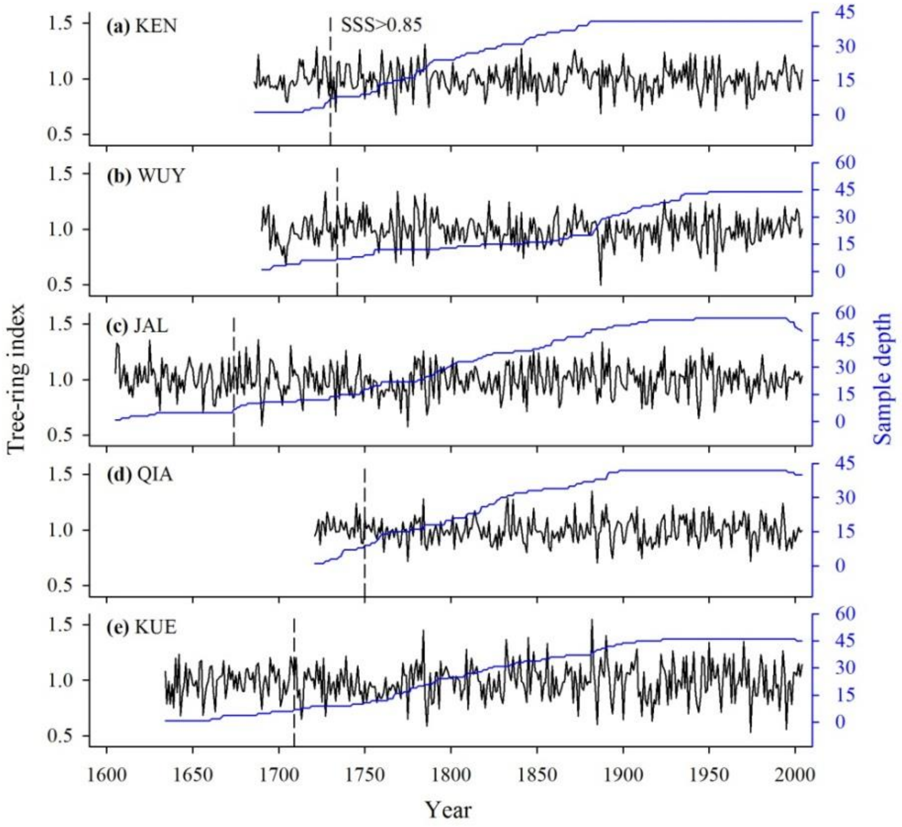

Fig. 4 Five residual tree-ring chronologies and the corresponding sample depth

Statistical analysis

To investigate the difference in tree-ring chronology characteristics at different altitudinal sites, the following statistical parameters were computed to compare the five residual chronologies (Table 4): mean ring width (MW), mean series length (ML), maximum series length (MA), mean sensitivity (MS), standard deviation (SD), first-order autocorrelation (AC1), mean inter-series correlation (MR), the variance explained by the first principal component (PC#1), expressed population signal (EPS), and signal-to-noise ratio (SNR) (Fritts 1976).

A correlation matrix of the five residual chronologies was created over the common reliable period 1750–2004 (Table 5) to assess the degree of similarity in growth variability between different altitudes. Moreover, a rotated principal component analysis (RPCA) was used as a clustering technique to test groups of the five chronologies and to determine whether the similarities and/or differences among the chronologies were related to site elevations. RPCA is based on principal component analysis (PCA), which is a data reduction technique for extracting the dominant modes of orthogonal variation within a dataset (Richman 1986; Cook et al. 2001). The number of components retained for further analysis was determined according to the Kaiser–Guttman criterion (i.e., eigenvalues greater than 1.0) (Jackson 1993; Oberhuber and Kofler 2000), and the retained components were rotated orthogonally using the varimax procedure. This transformation serves to maximize the spread of individual loadings and thus produce more interpretable loadings (Richman 1986).

Simple correlation analysis was employed to investigate the climate–growth relationships for each site. The correlation coefficients between the tree-ring chronologies and the monthly climate data were calculated over their common period 1960–2004. Considering that tree growth could be influenced by climate conditions in the current and previous years (Fritts 1976), correlation analysis was performed for an 18-month interval from May of the previous growth year to October of the current growth year. In addition, we calculated the correlation coefficients of chronologies with various seasonal aggregates of climate variables to further investigate the climate influence on tree growth in the study area.

Results

Statistical characteristics of the five chronologies

The statistical characteristics of the five chronologies were shown in Table 4. The mean ring width (MW) at the KUE and QIA sites was larger than that at the other sites. Mean series length (ML) varied slightly between different sites, except for WUY, which had more relatively short series (Fig. 4b). Maximum series length (MA) ranged from 284 to 400 years, with the smallest value at the QIA site. The mean ring width (MW), mean sensitivity (MS), standard deviation (SD), mean inter-series correlation (MR) and the variance explained by the first principal component (PC#1) generally decreased with increasing elevation at the low-, mid- and high-elevation sites, except for QIA, which had the largest MW and the smallest MS, SD, MR, and PC#1. All the five chronologies showed high EPS and SNR, indicating that these chronologies have good qualities to study the correlation between tree growth and climate factors. According to SSS threshold value of 0.85, the five chronologies held the common reliable period of 1750–2004 (Table 4).

Table 4 General statistics for tree-ring chronologies from the five different altitudinal sites

	KUE	QIA	JAL	WUY	KEN
MW [a] (mm)	1.746±0.691	1.919±0.616	1.427±0.495	1.328±0.668	1.255±0.419
ML [a] (year)	210±73	201±53	218±85	160±81	214±51
MA (year)	371	284	400	315	319
MS	0.183	0.126	0.170	0.155	0.144
SD	0.160	0.112	0.139	0.129	0.119
AC1	0.042	0.051	-0.134	-0.121	-0.170
MR	0.438	0.318	0.426	0.383	0.400
PC#1 (%)	47.1	34.4	44.4	41.0	42.0
EPS	0.972	0.950	0.974	0.952	0.965
SNR	34.226	19.130	37.852	19.857	27.305
SSS>0.85	1709–2004	1750–2004	1674–2004	1734–2004	1730–2004

[a] Data are presented in Mean ± SD (standard deviation)

Comparisons of the tree-ring chronologies

The correlation matrix of the five chronologies for the common reliable period (1750–2004) was shown in Table 5. The correlations between the two low-elevation chronologies (KUE and QIA) as well as the two high-elevation chronologies (WUY and KEN) were both very high, with correlation coefficients of 0.806 (*p*<0.01) and 0.794 (*p*<0.01), respectively. By contrast, the correlations between the low- and high-elevation chronologies (KUE and WUY, QIA and WUY, QIA and KEN, KUE and KEN) were much lower. The correlations between the mid- and low-elevation chronologies (JAL and KUE, JAL and QIA) as well as the high-elevation chronologies (JAL and WUY, JAL and KEN) were in-between, with correlation coefficients from 0.516 (*p*<0.01) to 0.655 (*p*<0.01).

Table 5 Correlation matrix of the five residual chronologies over the common reliable period 1750–2004

	KUE	QIA	JAL	WUY	KEN
KUE	1				
QIA	0.806**	1			
JAL	0.612**	0.655**	1		
WUY	0.120	0.201**	0.553**	1	
KEN	0.121	0.202**	0.516**	0.794**	1

** Correlation is significant at the 0.01 level (2-tailed)

RPCA performed on the five chronologies over the common reliable period (1750–2004) showed that the eigenvalues of the first two components (PCs) were greater than 1.0 (Table 6). Therefore, the first two PCs, explaining 86.894% of the total variance among the five chronologies, were retained and rotated by the varimax method to produce more spatially interpretable loadings. As shown in Fig. 5, the rotated varimax loadings clearly illustrated the separation of the five chronologies into three groups. The first PC, yielding high loadings for KUE and QIA but low loadings for WUY and KEN, could represent the low-elevation sites. The second PC, yielding high loadings for WUY and KEN but low loadings for KUE and QIA, could represent the high-elevation sites. The mid-elevation site (JAL) had medium loadings for both PCs, and represented a transitional site between the low- and high-elevation sites.

Table 6 Rotated PCA of the five tree-ring chronologies for the period 1750–2004

Component	Initial	Rotated [a]

	Eigenvalue	% Variance	Cumulative %	Eigenvalue	% Variance	Cumulative %
1	2.860	57.210	57.210	2.279	45.576	45.576
2	1.484	29.684	86.894	2.066	41.318	86.894
3	0.268	5.363	92.257			
4	0.198	3.953	96.210			
5	0.189	3.790	100			

[a] First two components with eigenvalues > 1.0 are rotated

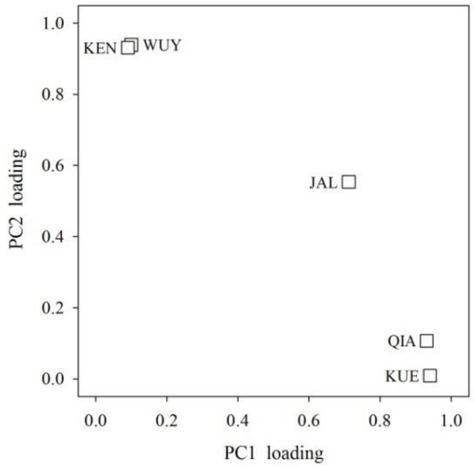

Fig. 5 Varimax loadings of the first and second PCs from the five chronologies, each square represents a site chronology

Climate–growth relationships

The correlations between tree-ring chronologies and monthly climate variables indicated that there were three different groups in the climate–growth correlation patterns (Fig. 6). The two low-elevation chronologies (KUE and QIA) generally showed high negative correlations with monthly mean, maximum and minimum temperatures in months during the previous and current growing seasons, and most of the highest correlations for each of these months occurred in mean or maximum temperatures. In contrast, most of the correlations between the two high-elevation chronologies (WUY and KEN) and the three temperature variables in these months were positive, and almost all of the highest correlations for each of these months occurred in minimum temperature. The correlations of the mid-elevation chronology (JAL) with the three temperature variables in these months were generally low, except for the significant negative correlations with mean and maximum temperatures in previous August. In other months, the high positive correlations were found in March for JAL and WUY, and February for KEN. For precipitation and PDSI, the low- and mid-elevation chronologies (KUE, QIA and JAL) had high positive correlations with precipitation in months during the previous late and current early growing seasons. While the two high-elevation chronologies (WUY and KEN) had high positive correlations with precipitation in several months prior to the growing season, and negative correlations in current September. However, only the two low-elevation chronologies (KUE and QIA) showed high positive correlations with growing season PDSI.

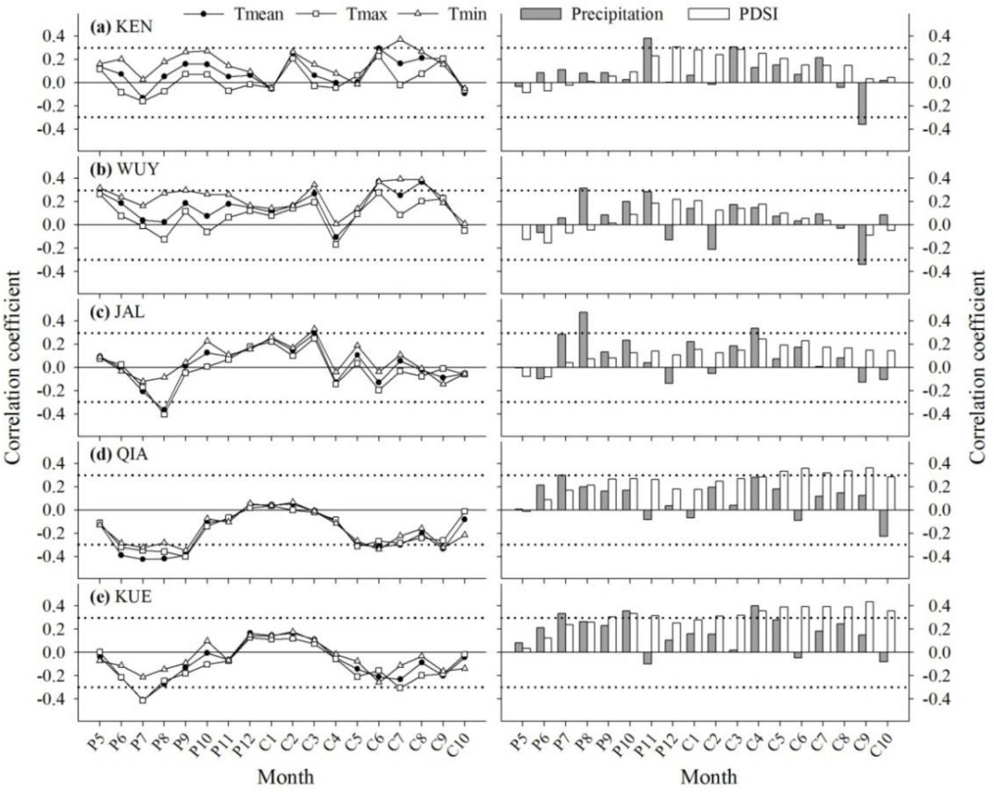

Fig. 6 Correlation coefficients between the five tree-ring chronologies and monthly mean temperature (Tmean), monthly maximum temperature (Tmax), monthly minimum temperature (Tmin), monthly total precipitation, and monthly PDSI from the previous May (P5) to current October (C10) over the period 1960–2004. The *horizontal dotted lines* indicate 95 % confidence level

The correlations between tree-ring chronologies and seasonal climate data were shown in Table 7. The two low-elevation chronologies (KUE and QIA) showed high negative correlations with temperatures (particularly mean and maximum temperatures) in previous and current June–August. While the two high-elevation chronologies (WUY and KEN) showed high positive correlations with temperatures (particularly mean and minimum temperatures) in current June–August. The positive correlations of tree growth with seasonal and annual precipitation (from previous July to current May) were higher at the low- and mid-elevation sites (KUE, QIA and JAL) than that at the high-elevation sites (WUY and KEN). The correlations of tree growth with growing season PDSI (current April–September) were significant at the low-elevation sites (KUE and QIA), but not evident at other sites. The correlation analyses between seasonal climate and the rotated PC1 and PC2 represented the common growth response to regional climate of low-elevation sites and high-elevation sites, respectively. The results were in agreement with the response patterns calculated from the individual chronologies.

Table 7 Correlation coefficients between seasonal climate data and the five chronologies as well as the rotated PC1 and PC2 series over the common period 1960–2004

	KUE	QIA	JAL	WUY	KEN	PC1	PC2
P6–P8 Tmean	-0.435**	-0.602**	-0.287	0.125	0.003	-0.546**	0.173
P6–P8 Tmax	-0.441**	-0.521**	-0.288	-0.032	-0.163	-0.486**	0.008
P6–P8 Tmin	-0.179	-0.344*	-0.091	0.268	0.164	-0.295	0.272
C6–C8 Tmean	-0.256	-0.400**	-0.053	0.499**	0.333*	-0.384*	0.496**
C6–C8 Tmax	-0.334*	-0.403**	-0.155	0.294	0.145	-0.410**	0.303*
C6–C8 Tmin	-0.157	-0.282	0.019	0.454**	0.349*	-0.267	0.460**
P7–P8 Pre	0.369*	0.308*	0.442**	0.205	0.117	0.373*	0.118
C4–C5 Pre	0.470**	0.319*	0.289	0.154	0.191	0.397**	0.086
P7–C5 Pre	0.581**	0.398**	0.492**	0.309*	0.304*	0.501**	0.217
C4–C9 PDSI	0.414**	0.349*	0.198	0.041	0.156	0.378*	0.009

Tmean mean temperature, *Tmax* maximum temperature, *Tmin* minimum temperature, *Pre* precipitation, *P6–P8* previous June to August; *C6–C8* current June to August; *P7–P8* previous July to August; *C4–C5* current April to May; *P7–C5* previous July to current May; *C4–C9* current

April to September

* correlation is significant at the 0.05 level (2-tailed)

** Correlation is significant at the 0.01 level (2-tailed)

Discussion

The statistical characteristics of the five chronologies showed some elevation-dependent variations at the low-, mid- and high-elevation sites, except for the QIA site. Considering that all sites had approximately similar canopy density, soil depth, slope and exposure, the influence of these factors on tree growth was excluded in this study. The largest value of MW at the QIA site might partly result from tree age, as inferred from the smallest value of MA at this site (Table 4). Another possible explanation was that the QIA site had better climate conditions for *P. schrenkiana* growth, as indicated by the largest MW but the smallest MS, SD, MR and PC#1 at this site. The decrease of MW, MS, SD, MR and PC#1 with increasing elevation was frequently reported in previous studies (e.g., Fritts et al. 1965; LaMarche 1974; Gou et al. 2005; Wang et al. 2005; Gao et al. 2013). This was probably the result of a decrease in temperature and in the length of the growing season with increasing elevation. The lower temperature and a shorter growing season in high elevations may lead to trees showing low metabolic rate to adapt to the environment (Di Filippo et al. 2007).

The results of correlation matrix and RPCA suggested that elevation played a crucial role in determining tree growth patterns in the study area. The climate–growth relationships also changed along the altitudinal gradient (Fig. 6). Humidity and thermal conditions generally change with the elevation in mountainous region, which might result in the changed climate–growth relationships and thus the elevation-dependent tree growth patterns. In the Tianshan Mountains, *P. schrenkiana* is a hygrophilous and shade-tolerant tree species (Yuan et al. 2001). Precipitation during the previous late and current early growing seasons exerted an important role on tree growth at the low- and mid-elevation sites (Wang et al. 2005; Guo et al. 2007). High precipitation during the growing season most likely enhances photosynthetic rate and thus increases tree growth. While high temperatures during this period could decrease tree growth due to increased evapotranspiration and water deficit (Wang et al. 2005). The significant positive correlations of tree growth with growing season PDSI confirmed the important role of moisture in regulating the growth of *P. schrenkiana*. Therefore, tree growth at the low-elevation sites was mainly limited by moisture availability.

With increasing altitude, it was colder at the high-elevation sites than at the low-elevation sites. The negative influence of temperature on tree growth was disappeared, and temperature exerted positive effect on tree growth at the high-elevation sites. Warmer summer temperatures may promote earlier snow-melting and more rapid soil warming, thereby lengthening the snow-free growing season (Carrer et al. 2007). A warmer winter may prevent foliage damage (Wang et al. 2005), and protect the soil from a deep layer of frost which potentially delays the time of thawing and shortens the growing season (Yuan and Li 1999; Gao et al. 2013). Regarding the key role of minimum temperature (night-time temperature), a previous study indicated that compared with trees at lower elevation, high altitude treeline trees may “lose nights” for above-ground tissue formation (Körner and Paulsen 2004). Precipitation prior to the growing season exerted positive effect on tree growth. Wang et al. (2005) considered that with high soil moisture at the upper treeline, tree growth was influenced more by the amount of storage compounds rather than by the current soil moisture regime. Moreover, excessive precipitation in September was often accompanied by lower temperature, which may be related to a shorter growing season for high-elevation trees. Thus, tree growth at the high-elevation sites was mainly controlled by lower temperature, while precipitation prior to the growing season influenced tree growth with its indirect effect.

Based on the above analyses, it was concluded that there was obvious altitudinal effect on tree growth patterns and climate–growth relationships in the study area. Yang et al. (2013) considered that the importance of temperature or precipitation in controlling tree growth with respect to altitude likely depends on the general climate of the area, and the relatively arid conditions probably drive the consistent and coherent inter-annual variability of tree growth–climate relationships in the Qilian Mountains. Dittmar et al. (2003) suggested that varied climate–growth relationships most likely arose in response to the regional variations in climate along the altitudinal gradients and geographical variability of sites. Moreover, Fang et al. (2009b) indicated that the large altitudinal gradient would result in changing climate–growth correlation patterns at the Xinglong Mountain. In our study, the relatively humid conditions related to the special topography of Yili valley, together with the wide altitudinal range of *P. schrenkiana* forests probably resulted in the elevation-dependent climate–growth relationships in the study area. However, the explanatory power of the climate–growth relationships calculated might be limited by the available climate data, so further studies are needed to verify our results.

Conclusions

Five tree-ring width chronologies of *P. schrenkiana* were developed along an altitudinal gradient in the western Tianshan Mountains, and their radial growth variations and climate–growth relationships were investigated. The results suggested that elevation played a crucial role in determining tree growth patterns in this mountainous region. The changed limiting climatic factors associated with altitudinal gradient were suggested as determinants of elevation-dependent tree growth patterns. Moisture availability appeared to be the most important factor limiting tree growth at the low-elevation sites. With increasing altitude, the importance of precipitation decreased, tree growth at the high-elevation sites was mainly controlled by lower temperature. The regional climate conditions related to special topography, together with the wide altitudinal range of *P. schrenkiana* forests probably resulted in the elevation-dependent climate–growth relationships in the study area. However, more studies on tree growth at various elevations are needed in order to improve our understanding of the climate–growth relationships of *P. schrenkiana* and to provide more insights on its large-scale growth response to climate change.

Author contribution statement

Yuxia Huo analyzed the data and wrote the initial manuscript. Xiaohua Gou designed the research and revised the manuscript. Wenhuo Liu assisted with data analysis and helped interpret the data with Fen Zhang. Jinbao Li and Keyan Fang contributed to the field and laboratory works. All authors reviewed the manuscript.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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