ORIGINAL ARTICLE

Responses to climate change in radial growth of *Picea schrenkiana* along elevations of the eastern Tianshan Mountains, northwest China

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ARTICLE INFO

Article history:
Received 25 April 2016
Received in revised form 26 August 2016
Accepted 11 September 2016
Available online 20 September 2016

Keywords:
Climate change
Growth response
Dendroclimatology
Elevation gradient
Drought stress
Eastern tianshan mountains

ABSTRACT

Tree growth is largely driven by climate conditions in arid and alpine areas. A strong change in climate from warm-dry to warm-wet has already been observed in northwest China. However, little is known about the impacts of regional climate variability on the radial growth of trees along elevations of the eastern Tianshan Mountains. Consequently, we developed three tree-ring width chronologies of Schrenk spruce (*Picea schrenkiana* Fisch. et Mey.) ranging in elevation from 2159 to 2552 m above sea level (a.s.l.), which play an important role in the forestry ecosystem, agriculture, and local economy of Central Asia. In our study, the correlation analyses of growth-drought using the monthly standardized precipitation-evapotranspiration index (SPEI) at different temporal scales demonstrated that drought in growing season was the main factor limiting tree growth, regardless of elevation. The relationships between radial growth of Schrenk spruce and main climate factors were relatively stable by moving correlation function, and the trend of STD chronologies and basal area increment (BAI) also showed a synchronous decline across the three elevations in recent decades. And meanwhile, slight differences in responses to climate change in radial growth along elevations were examined. The drought stress increased as elevations decreased. Radial growth at the higher elevation depended on moisture availability due to high temperature, as indicated by the significant negative correlation with mean temperature in the late growing season of the previous year (August-September, p < 0.001). However, radial growth at the lower elevation were restricted by drought stress due to less precipitation and higher temperatures, as demonstrated by the significant negative correlation with mean temperature but positive with total precipitation in the early growing season of the current year (April-May, p < 0.05). In addition, the decline of radial growth (BAI) at the higher elevation (3.710 cm² yr⁻¹/decade, p < 0.001) was faster than that of the middle elevation (2.344 cm² yr⁻¹/decade, p < 0.001) and the lower elevation (3.005 cm² yr⁻¹/decade, p < 0.001) since 2000, indicating that the trees at higher elevation of a relatively humid environment were more susceptible to the effects of climate change due to their poor adaptability to water deficit. Therefore, the forest ecosystems would be suppressed as a result of increasing drought stress in the future, especially in the high-elevation forests of arid and semi-arid areas.

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1. Introduction

Climate change and its impacts on forest ecosystems are a major force in the twenty-first century (Engelbrecht, 2012; IPCC, 2013). During the past 50 years, the climate in northwest China has changed from warm-dry to warm-wet due to an enhanced global warming and water cycle, most notably in the Xinjiang area (Shi et al., 2007). This climate change is embodied by the increase in total precipitation of 10.15 mm/decade and by a 0.33 °C/decade increase in air temperature during 1960–2010, as measured by 51 meteorological stations in northwest China (Li et al., 2013). This rising trend of annual mean temperature in northwest China was higher than the increasing average of the entire country of China (0.25 °C/decade) and that of the entire globe (0.13 °C/decade) for the same period (Li et al., 2012a).

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http://dx.doi.org/10.1016/j.dendro.2016.09.002

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northwestern China include increased glacial melt water, flood disasters, and vegetation cover and the reduction of sand-dust storm days (Shi et al., 2007).

The forest ecosystems, covering approximately 30% of the Earth’s total land surface, perform a multitude of the ecological service functions such as terrestrial carbon pools, fresh water cycles, biodiversity, and so on (King et al., 2013). Due to their long life spans and sensitivity to climate factors, forests are considered to have limited adaptability (Lindner et al., 2010). Hence, the spatiotemporal variations of climate have likely impacted the compositions and functions of forest ecosystems in recent decades (Hartl-Meier et al., 2014a). For example, the loss of forest productivity and increase in susceptibility to disturbances in the eastern Alps and the severe degradation in the Normalized Difference Vegetation Index (NDVI) in northern Kazakhstan were shown to be due to drought stress with continued warming during recent decades (Seidl et al., 2011; Gessner et al., 2013). However, vegetation productivity increased in northern Xinjiang after the 1980s according to remote sensing studies (Piao et al., 2005). Therefore, there is still a high degree of uncertainty for the development of forests under climate change, and the effects will depend on the characteristics in different regions and species-specific tolerances (Elkin et al., 2013).

Elevation is an important factor affecting tree growth in mountains with variable climate and terrain, and forest ecosystems in mountains are widely considered to be sensors of climate variability (Malanson et al., 2011; Wang et al., 2015b). In general, radial growth of trees in arid and semi-arid areas correlates positively with temperature at the higher elevation and is limited by drought at the lower elevation (Fritts and Budelsky, 1965). Many dendrochronological studies have confirmed this elevation-dependent response pattern (Wilson and Hopfmüller, 2001; Zhang et al., 2012). In contrast to this general hypothesis, several studies have observed different results along elevations. For example, the spring and summer drought was the emergent limiting factor of Pinus uncinata at the higher elevations in the Iberian and of Betula utilis in the upper timberlines of the Himalayas (Liang et al., 2014; Diego Galván et al., 2015). Similar correlation patterns of Sabina tibetica and Sabina przewalskii with climate factors at the high- and low-elevation sites of south and Northeast Tibetan were also shown (Liu et al., 2013; Qin et al., 2013). Based on the radial growth response to climate factors along elevations of dendroclimatology, global warming is believed to have positive effects on forests at the higher elevation but negative effects at the lower elevation, as observed in the Alps of Europe (Paulsen et al., 2000), the Tatra Mountains of Poland (Savva et al., 2006), the western mountains of North America (Salzer et al., 2009), eastern Siberia (Tei et al., 2014), the Andes of northern Patagonia (Álvarez et al., 2015), and the Shennongjia Mountains of central China (Dang et al., 2013).
However, some other results were inconsistent with this general hypothesis. For example, Abies faxoniana showed sustained reduction at the higher elevation of the Balang Mountains in China’s Western Sichuan Province during the late 20th century (Li et al., 2012b). Norway spruce was still robust under climate change without growth suppression at the lower elevation of the European Alps (Hartl-Meier et al., 2014b). Therefore, the responses of tree radial growth to climate change should be carefully evaluated along elevations, and their physiological mechanisms need to be explored in various mountain ecosystems (He et al., 2013).

The variations in tree-ring width are mainly influenced by climate factors (Fritts, 1976). Therefore, dendrochronology using tree-ring width is a good method for reconstructing historical climate, interpreting biological responses to climate factors, assessing the stability of growth-climate relationships, and analyzing growth patterns under climate change (Fang et al., 2012). The Tianshan Mountains in Xinjiang of northwest China play an important role in the ecosystem of Central Asia. Compared to the western and central Tianshan Mountains, the eastern Tianshan Mountains are the driest regions and are ideal for studying tree growth-climate relationships (Chen et al., 2015). A few dendrochronological studies have been carried out in the eastern Tianshan Mountains, but they focused mainly on climate reconstruction (Wang et al., 2007; Xu et al., 2014; Chen et al., 2015), environmental response of tree-ring width and stable carbon isotope at the upper tree line (Shang et al., 2010), and divergent responses of radial growth for Larix sibirica to climate warming (Jiao et al., 2015). The response distinctions of radial growth to climate change along elevations have not been studied in the eastern Tianshan Mountains. In this context, it is crucial to (1) identify major climate factors controlling the radial growth of Schrenk spruce, (2) investigate radial growth responses to climate factors along elevations, and (3) assess the effects of climate change on the patterns of trees growth in the eastern Tianshan Mountains.

2. Materials and methods

2.1. Study area

The study area is located on the north side of the eastern Tianshan Mountains, northwest China (Fig. 1), in the interior of the Eurasian continent and dominated by drought with the central Asian westerly circulation (Xu et al., 2014). During the period 1960–2012, meteorological records from the Barkol station (43°36’ N, 93°03’ E, 1677 m a.s.l.) indicated that the total annual precipitation averages 220.9 mm, 73.5% of which falls in the spring and summer (from March to August). The mean annual temperature was 2.1 °C, the warmest mean monthly temperature was 18.1 °C in July, and the coldest mean monthly temperature was −17.6 °C in January (Fig. 2). Schrenk spruce and Siberian larch (Larix sibirica Ledeb.) are the dominant species in the study area (Peng et al., 2005). This study focused on Schrenk spruce, which is an evergreen species that is preferentially distributed on shady slopes at altitudes of 2100–2600 m a.s.l. of the eastern Tianshan Mountains (Wu et al., 2015b).

2.2. Meteorological data

Precipitation and temperature data were obtained from the Barkol meteorological station closest to the study regions (approximately 12 km) (Fig. 1). A linear regression model of recorded climate data showed that the total annual precipitation had a significant increasing trend of 10.65 mm/decade (p = 0.008), while the mean annual temperature showed a similar increasing trend of 0.63 °C/decade (p < 0.001) over the period 1960–2012 (Fig. 3). Tree growth was affected not only by the climatic conditions of the current year but also by those of the previous year (Fritts, 1976), so the monthly climate data from August of the previous year to September of the current year were used for growth-climate relationship analysis.

The monthly standardized precipitation-evapotranspiration index (SPEI) data were calculated using climate data (precipitation, temperature, relative humidity, solar radiation, water vapor pressure, and wind speed) with the SPEI calculator (Vicente-Serrano et al., 2010). The SPEI has advantages over other drought indices, such as the standardized precipitation index (SPI) and the Palmer Drought Severity Index (PDSI); the SPI neglects the effect of temperature on drought, and the PDSI lacks the multi-scale character (DeSoto et al., 2014; Diego Galván et al., 2015). Negative SPEI values correspond to dry conditions and positive represent wet conditions.

2.3. Field sampling

Tree-ring samples of Schrenk spruce were collected from a consistent north-facing slope of Heixi valley with three elevations.

<table>
<thead>
<tr>
<th>Site</th>
<th>Elevation (m)</th>
<th>Latitude (N)</th>
<th>Longitude (E)</th>
<th>Slope</th>
<th>Exposure</th>
<th>CC (%)</th>
<th>TD (m)</th>
<th>DBH (cm)</th>
<th>TH (m)</th>
<th>CW (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>bk1 P1</td>
<td>2552</td>
<td>N 43°32.100’</td>
<td>E 92°56.329’</td>
<td>27°</td>
<td>North</td>
<td>30</td>
<td>3.0</td>
<td>32.4</td>
<td>12.3</td>
<td>2.7</td>
</tr>
<tr>
<td>bk2 P1</td>
<td>2334</td>
<td>N 43°32.324’</td>
<td>E 92°56.239’</td>
<td>13°</td>
<td>East</td>
<td>30</td>
<td>2.0</td>
<td>16.6</td>
<td>10.2</td>
<td>2.7</td>
</tr>
<tr>
<td>bk3 P2</td>
<td>2159</td>
<td>N 43°32.695’</td>
<td>E 92°56.235’</td>
<td>8°</td>
<td>North</td>
<td>20</td>
<td>2.0</td>
<td>24.0</td>
<td>10.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Barkol Station</td>
<td>1677</td>
<td>N 43°36’</td>
<td>E 93°03’</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

ranges: near the upper timberline of spruce forests (2552 m a.s.l.) of blk(P)1, the middle elevation (2334 m a.s.l.) of blk(P)2, and the lower elevation (2159 m a.s.l.) of blk(P)3 (Fig. 1 and Table 1). The slopes (8° to 27°) and the canopy coverages (approximately 20% to 30%) increased as elevation increased. Trees were sparser, higher and sturdier at the higher elevation than at the middle and lower elevations. In each study area, 25 healthy old trees located in relatively sparse or isolated conditions were sampled without non-climatic impacts of fire, disease, insect infestation, and human disturbance. Two cores per tree at a height of 1.3 m were extracted at 120° from each other with a 5.15-mm-diameter increment borer. A total of 150 cores from 75 living trees were collected in August 2013.

2.4. Tree-ring chronology development

Tree cores were air-dried, mounted on woody supports, and polished with 120-, 400-, and 600-gritted sandpapers until tree rings were clearly visible (Stokes and Smiley, 1968). Each tree-ring width was measured with a resolution of 0.001 mm using the LINTAB measurement system (TMS, Rintech, Heidelberg, Germany). The quality of the cross-dating was determined using the COFECHA program (Holmes, 1983). Because of significant deviations, two series of blk(P)1 were excluded from the master chronology. The raw tree-ring width series were detrended by the negative exponential curve or by linear regression, and then the standard chronologies (STD) were developed by averaging all individual tree core chronologies with a bi-weight robust mean utilizing the ARSTAN program (Cook, 1985). The STD chronology contained the strong climate signals and removed non-climatic growth effects from age-related growth trend, autocorrelation and possible other disturbances (Fritts, 1976).

Several statistical parameters were calculated to analyze the variability of the series and test the quality of chronologies (common period: 1960–2012), including MS, SD, AC1, R, PCI, SNR, and EPS (Table 2). MS characterizes the variability intensity of year-to-year ring width. SD estimates the variability of each series. AC1 detects the persistence retained from previous growth. R expresses the degree of common signals among all series. PCI indicates the percentage of variance explained by the first component in principal component analysis. SNR and EPS estimate the climatic information strength in the developed chronologies, and EPS > 0.85 is generally considered a threshold value of reliable chronology (Fritts and Shatz, 1975; Wigley et al., 1984).

The Gleichläufigkeit index (GLK) was calculated to examine the similarity between any two chronologies (Schweingruber, 1988). The percentage of total GLK represents the consistency of two chronological curves at a very high frequency (Wang et al., 2013). A high GLK value represents the similarity of growth patterns and factors limiting growth (Zhang et al., 2012).

2.5. Analysis of growth–climate relationship

For each sample site, we calculated the Pearson correlation coefficients between tree-ring width chronology and monthly climatic factors (total precipitation and mean temperature) during 1960–2012. To analyze the influence of drought duration and intensity on tree growth, we also calculated the Pearson correlation coefficients between tree-ring width chronology and SPEI at different time scales from 1 to 24 accumulated months. Positive coefficients indicate that the tree radial growth is strongly impacted by drought, whereas negative coefficients indicate that wet conditions were the limiting factors for radial growth of trees (DeSoto et al., 2014). Moreover, we used DendroClim 2002 to investigate the temporal stability of the growth–climate relationship with the moving correlation function, which could accurately depict the dynamic responses of radial growth to climate change (Biondi and Waikul, 2004). The moving correlation function calculated correlation coefficients between tree-ring width chronologies and the climatic factors for a 24-year period, which slid progressively backward each year starting from 1960 with a bootstrap procedure adopting 1000 replications.
2.6. Evaluation of the tree radial growth trend

We analyzed the tree radial growth trend by evaluating STD chronologies and calculating the basal area increment (BAI, cm² yr⁻¹) along elevations. STD chronology contains abundant low-frequency information and BAI represents consecutive cross-sectional basal areas as the indicator of growth speed, which is suitable for the evaluation on radial growth pattern (Qi et al., 2015). The decreasing trend in BAI is indicative of an effective decline of tree growth under environmental stress (Gazol et al., 2015; Rodríguez-Catón et al., 2015). BAI was calculated based on non-standardized raw measurement ring width data as the following equation:

\[ BAI_t = \pi (r_t^2 - r_{t-1}^2) \]  (1),

where \( r_t \) is a given annual ring corresponding to radial radius at year \( t \) and \( r_{t-1} \) is a given annual ring corresponding to radial radius at year \( t-1 \) (Monserud and Sterba, 1996).

3. Results

3.1. Tree-ring chronology characteristics at different elevations

We paid attention to SNR of three elevations with higher values and EPS exceeding the threshold of 0.850, suggesting that the chronologies of three elevations were more reliable (Table 2). Meanwhile we found MS, R1 and PC1 for blk[P]3 chronology were also higher than blk[P]1 and blk[P]2, indicating that the radial growth of trees at the lower elevation contained stronger signals and was more sensitive to climate than the middle and higher elevations (Table 2). In addition, AC1 for blk[P]2 and blk[P]1
chronologies were higher than that of blk(P)3, demonstrating that the current year’s radial growth of trees at middle and higher elevations were more affected by the previous year’s climate than that of the lower elevation.

Based on the GLK indices, the chronologies for blk(P)2 and blk(P)3 had the highest similarity, with a value reaching 88.7% (p < 0.001) (Fig. 4). Conversely, there were also relatively high similarities for the chronologies of blk(P)1-blk(P)2 and blk(P)1-blk(P)3: 78.6% and 81.1%, respectively (p < 0.001). Analyzing the results of GLK indices, the year-to-year variations of radial growth for Schrenk spruce were relatively consistent over different elevations, especially for two lower adjacent elevations.

3.2. Climate–growth relationships along elevations

3.2.1. Relationships between radial growth and total precipitation and mean temperature

Tree-ring width chronologies along elevations revealed uniform climate responses across the three elevations, showing significant positive correlations with total precipitation and significant negative correlations with mean temperature (Fig. 5). However, the correlation coefficients between chronologies and specific climate factors varied by elevation.

The tree-ring width chronology for blk(P)1 at the higher elevation exhibited a positive response to total precipitation in November of the previous year \((r = 0.276, p < 0.05)\) but exhibited negative responses to mean temperatures from August to November of the previous year \((r = −0.297, p < 0.05)\) and March to September of the current year \((r = −0.322, p < 0.05)\). The tree-ring width chronology for blk(P)2 at the middle elevation exhibited a negative response to total precipitation in August of the current year \((r = −0.295, p < 0.05)\) and negative responses to mean temperatures in August \((r = −0.345, p < 0.05)\), September \((r = −0.288, p < 0.05)\), and November \((r = −0.309, p < 0.05)\) of the previous year and from April to July of the current year \((r = −0.269, p < 0.05)\). The tree-ring width chronology for blk(P)3 at lower elevation exhibited positive responses to total precipitation in April \((r = 0.287, p < 0.05)\) and June \((r = 0.283, p < 0.05)\) of the current year but exhibited negative responses to mean temperatures in August \((r = −0.315, p < 0.05)\) and September \((r = −0.309, p < 0.05)\) of the previous year and March \((r = −0.329, p < 0.05)\), April \((r = −0.324, p < 0.05)\), May \((r = −0.544, p < 0.01)\), July \((r = −0.378, p < 0.01)\), and August \((r = −0.288, p < 0.05)\) of the current year.

With respect to the seasonal and annual climate factors, the tree-ring width chronology for blk(P)1 was negatively influenced by mean temperature in the non-growing season, growing season and annual \((p < 0.01)\), especially the late growing season of the previous year \((August–September, r = −0.735, p < 0.001)\). And meanwhile, the tree-ring width chronologies for blk(P)2 and blk(P)3 were negatively influenced by mean temperature in growing season and annual \((p < 0.05)\), especially the early growing season of the current year \((April–May, r = −0.438 and −0.505, p < 0.001)\). But the tree-ring width chronology for blk(P)2 was negatively influenced by total precipitation in the late growing season of the current year \((August–September, r = −0.358, p < 0.009)\), and blk(P)3 was positively influenced by total precipitation in the early and middle growing season of the current year \((April–May, r = 0.327, p < 0.05; June–July, r = 0.283, p < 0.05)\).

3.2.2. Relationships between radial growth and SPEI

As shown in Fig. 5. Tree-ring width negative correlation with temperature and positive correlation with precipitation suggested the drought was a dominant influence factors for radial growth. Therefore, we explored the correlations of tree-ring width chronologies with the SPEI drought indices at different time scales, taking both precipitation and evapotranspiration into account. Overall, different patterns of correlation between SPEI and chronologies were found at the three elevations (Fig. 6). At the higher elevation, the chronology for blk(P)1 had positive responses to SPEI at a 2- to 4-month scale accumulated from August to September of the previous year, a 6- to 8-month scale accumulated from November to December of the previous year, and a 10- to 16-month scale accumulated from March to September of the current year. At the middle elevation, the chronology for blk(P)2 had positive responses to SPEI at a 1- to 18-month scale accumulated from April to September of the current year. At the lower elevation, the chronology for blk(P)3 had positive responses to SPEI at a 1- to 24-month scale accumulated from March to September of the current year.

3.2.3. Stability of climate–growth relationships

The dynamic dimension responses of radial growth to climate factors were evaluated by the moving correlation function during the period of 1960–2012 (Fig. 7). At the higher elevation, a negative correlations between the chronology for blk(P)1 and mean temperatures in August and September of the previous year were stable. At the middle elevation, a stable positive correlation was found between the chronology for blk(P)2 and total precipitation in May of the current year, and a stable negative correlation was found between the chronology and mean temperature in May of the current year. At the lower elevation, stable positive correlations between the chronology for blk(P)3 and total precipitation in April and May of the current year, and stable negative correlations
between the chronology and mean temperatures of the current May and July were also confirmed.

3.3. **Radial growth trends at different elevations**

We found that the total precipitation in April–May and August–September of the current year, and the mean temperature in August–September of the previous year and April–May of the current year were the main factors limiting radial growth (Fig. 5). Therefore, we analyzed the trends of radial growth (STD chronologies and BAI) and limiting climate factors during the growing season using the linear regression for a 10-year moving average (Fig. 8). The results showed that all trends of main climate factors limiting radial growth have been significantly increasing \( (p < 0.001) \) since 1960 (Fig. 8A). However, the trends of radial growth at the three elevations were significantly decreasing during the same period (Fig. 8B and C). Meanwhile, the decline of radial growth (BAI) at higher elevation \( (3.710 \text{ cm}^2 \text{ yr}^{-1}/\text{decade}, p < 0.001) \) was faster than those of the middle elevation \( (2.344 \text{ cm}^2 \text{ yr}^{-1}/\text{decade}, p < 0.001) \) and the lower elevation \( (3.005 \text{ cm}^2 \text{ yr}^{-1}/\text{decade}, p < 0.001) \) after 2000.

4. **Discussion**

4.1. **Main factor driving radial growth of Schrenk spruce in eastern Tianshan Mountains**

The precipitation and temperature in recent decades have increased noticeably in northwest China, and the climate changed from warm-dry to warm-wet due to global warming (Shi et al., 2007; Yao et al., 2015). Therefore, the recent climate change had been a driver affecting the ecological and physiological processes of forest ecosystems in the mountains of northwest China (Li et al.,
This effect is expected to modify responses of radial growth to climate factors, showing variation in intensity and stability across different elevations. Here, we studied the responses of radial growth of Schrenk spruce to climate conditions across elevations and confirmed that drought was a main limiting factor for radial growth of coniferous trees in the eastern Tianshan Mountains.

Drought is one of the most severe manifestations of climate variability in China (Piao et al., 2010). Because total precipitation is very low, coupling ocean-atmosphere dynamics in the tropics, the available water in arid Central Asia can hardly meet the demand of the plants (Li et al., 2010). The Schrenk spruce growing in the study areas faces moisture stress and is often thought to be sensitive to warming-induced drought (Zhang et al., 2016). The positive responses of the radial growth to SPEI at the higher elevation of our study regions support this conclusion (Fig. 6). This growth response clearly differed from the behavior of conifers at higher elevation of most alpines including the western and central Tianshan Mountains, where growth was primarily controlled by the low air temperature rather than by drought (Cook and Kairiukstis, 1990; Guo et al., 2007; Wu et al., 2015b). Total annual precipitation is relatively small in the Tianshan Mountains of the central Asian interior and decreases slightly from west to east, meaning the eastern part suffers from more severe drought stress than the western and central parts (Figs. 2 and 3). The steep slope and high solar radiation coupled with a relatively open canopy at higher elevation could lead to high evaporative water loss and low water-holding capacity in our study regions (Table 1). Gradual climate warming might also result in a net decline in photosynthesis with increased respiration rates and reduced stomatal conductance, explaining that radial growth was more contingent on drought stress (Wu et al., 2015a). Liang et al. (2016) reported similar growth responses for stem increment variation, missing ring frequency, and tree mortality rate of Picea crassifolia that were typically limited by moisture availability in upper forests close to the alpine treeline of central Qilian Mountains, providing compelling evidence to support our study results.

We also found that drought stress increased as elevations decreased. Additionally, the drought of short and intermediate time-scales in growing seasons had a greater influence on the radial growth of Schrenk spruce at the higher elevation, whereas the growth at the lower elevation had been affected by both the short, intermediate and long time-scale droughts (Fig. 6). Compared with the higher elevation, there were worsening drought stresses due to less precipitation and higher temperature at the middle and lower elevations, leading to enhanced sensibility of radial growth to moisture availability (Hartl-Meier et al., 2014a). In addition, drought might pose a risk of increasing forest damage from outbreaks of pests, disease, and fire (Volney and Fleming, 2000; Siegert et al., 2001). It seems reasonable to suggest that increasing the duration and intensity of the drought stress might have more severe effects on tree vitality (Elkin et al., 2013).

4.2. Elevation-dependent radial growth responses of Schrenk spruce to climate factors

Our data also suggested that radial growth responses of Schrenk spruce to drought stress were different across elevations (Fig. 5). The trees at the higher elevation exhibited significant negative responses to temperature during the growing season, especially the late growing season of the previous year. Additionally, the trees at the lower elevation correlated positively with precipitation and correlated negatively with temperature during the growing season, especially the early growing season of the current year. Hence, we believed that the limitation of radial tree growth at the higher elevation was mostly moisture stress caused by higher temperature in late growing seasons of the previous year, while trees at lower
elevations were limited by drought due to the combination of less precipitation and higher temperature in the early growing season of the current year.

Most trees of at the higher elevation showed a positive correlation with temperature because of the relatively high precipitation supporting radial growth (Jiang et al., 2014). Consequently, strong negative responses of the higher elevation species to temperatures in growing seasons were relatively rare (Figs. 5 and 8). The mean monthly temperature was related to the regulation of moisture availability, and the decreased available water might restrict radial growth of trees due to the increase in evaporation as the mean temperature increases (Spond et al., 2014). Furthermore, the radial growth of trees at the higher elevation was more affected by previous climate, and the higher temperatures in the previous August and September would decrease water storage, which could decrease photosynthetic rates, resulting in fewer carbohydrates allocated for radial growth of the following year (McDowell et al., 2008).

With decreasing elevation, the mean monthly temperature increased and total precipitation decreased, and trees showed a strong ‘drought-sensitive’ response from the current April to June (Fig. 5). Generally, optimal spring temperatures and precipitation benefit mountain pine growth (Palombo et al., 2014). Higher amounts of precipitation during the current spring might provide the necessary moisture for plants and reduce evaporation rates due to increased cloud cover, benefitting cambial cell division in the fast growing season in arid areas (Liu et al., 2004). However, warmer temperatures during the same period would directly limit tree radial growth by exacerbating the effects of water deficit stress due to enhanced evapotranspiration and earlier melting of accumulated snow from the previous winter (Fritts, 1976). Similar results also have been reported in previous dendroclimatic studies in central Asia for Sabina przewalskii of the Qilian Mountains (Gao et al., 2013), Pinus tabulaeformis of Inner Mongolia (Liu et al., 2011), and Schrenk spruce surrounding the Issyk-Kul Lake of Northeast Kyrgyzstan (Zhang et al., 2014).

4.3. Potential impacts of climate change on the radial growth of Schrenk spruce

The structure and function of vulnerable semi-arid forests would likely change substantially with warming-induced drought stress, which can be best estimated from the temporal stability of growth-climate relationships and the trends of tree radial growth (Root et al., 2003). The total annual precipitation increased significantly during 1960–2012 in our study regions (Fig. 3). However, the increase in annual precipitation was not accompanied by an equivalent increase in tree growth rates, because the already existing heat-induced moisture stress was not alleviated with the increased evaporation due to the rapid rise in temperature (Figs. 6 and 8 A). Evidences from tree-ring δ18O and PDSI have also confirmed that no trend developed toward a wetter climate during last two decades in the eastern Tianshan Mountains (Zou et al., 2005; Xu et al., 2014).

Because the physiology and growth of plants are strongly driven by environmental factors such as temperature and precipitation, climate change has already altered the adaptive strategies of plants (Mainali et al., 2015). The ‘divergence problem’ as the relationship between tree growth and temperature weakens has been found at the higher latitudes of the Northern Hemisphere (D’Arrigo et al., 2008). In addition, the radial growth of Siberian larch has exhibited divergent responses to temperatures of the growing season in the eastern Tianshan Mountains since the late 1980s (Jiao et al., 2015). Although the responses fluctuated slightly during the same time period, we identified relatively stable relationships between the radial growth of Schrenk spruce and the main controlling climate factors at three elevations (Fig. 7). Compared to Siberian larch, the Schrenk spruce lives at relatively lower elevation, where a more stable drought signal was apparent during the growing season (Peng et al., 2005). Meanwhile, the drought stress was obviously not relieved, and the main climate factors controlling the radial growth were not essentially changed in recent decades (Figs. 5 and 6). Therefore, the radial growth of Schrenk spruce did not show divergent responses to climate factors in the face of climate change.

In conclusion, tree growth trends were consistent with the growth-climate relationships in our study regions (Fig. 8). Coniferous trees were not able to adapt as rapidly in the subalpine of arid regions, which were considered to be particularly vulnerable to climate change (Lindner et al., 2010). There was evidence that increased drought stress associated with recent climate change had already led to reduced tree growth in Alaska (Barber et al., 2000), North America (Houssset et al., 2014), western Canada (Hogg et al., 2003), north Patagonia (Rodríguez-Catón et al., 2015), and Spain and southern Italy (Gazol et al., 2015). Since the 1950s, reduced recruitment of alpine juniper shrubs (Juniperus pingii var. wilsonii) at treelines was coincident with warmer and drier climates in the central Tibetan Plateau of northwest China (Wang et al., 2015a). Climate warming was expected to lead to reduced tree growth at the lower elevations and increased growth at the higher elevations, but our results illustrated that the trends of radial growth at three elevations showed a significant decrease for the last 53 years (Fig. 8). The GLK values of the three chronologies were highly similar, indicating the radial growth patterns of Schrenk spruce were relatively consistent at different elevations with same drought stress (Fig. 4). However, Siberian larch growth rates first increased and then decreased in the eastern Tianshan Mountains from 1958 to 2012 (Jiao et al., 2015). The radial growth of a coniferous tree has a lower allocation priority in the short term than root and foliage formation, which is highly linked to the accumulation of photosynthesis reserves for the subsequent growing season (King et al., 2013). The radial growth of Siberian larch in the current year depends on carbohydrate reserves from the previous year as with a deciduous conifer, which is more sensitive to climate change (Kagawa et al., 2006). Conversely, the radial growth of Schrenk spruce depends on the storage of photosynthetic carbohydrates for several years by retaining needles, which is resistant to environmental change. Meanwhile, the decrease in radial growth at higher elevation was fastest among three elevations after 2000 (p < 0.001) (Fig. 8). Under dry climate conditions, hygrophilous trees at the higher elevation close their stomata at an early stage to reduce the risk of hydraulic failure and may be unable to cope with more severe water stress due to prolonged and frequent dry conditions in the future (Lévesque et al., 2014). On the other hand, the significant increase in total precipitation would be upwading trees due to temporally relieving the drought stress at lower elevation since the late 1980s, where was more serious water deficit. Therefore, the effect of climate change on tree growth was more apparent at the higher elevation.

5. Conclusion

The type of climate in northwest China has changed from warm-dry to warm-wet in recent decades. Through the analysis on the responses of Schrenk spruce to climate change across elevations in the eastern Tianshan Mountains, our results showed the radial growth of Schrenk spruce clearly did not lose sensitivity to climate factors and drought in growing season was the main factor limiting tree growth at three elevations. However, the radial growth responses to the drought stress increased as elevations decreased, supporting radial growth at the higher elevation was dominated by temperature in the late growing season of the previous year, whereas both temperature and precipitation in the early growing
season of the current year were more important drivers for radial growth of trees at the lower elevation. The declining trend of radial growth across the three elevations would imply that the structure and function of forests might be damaged. Meanwhile, the tree mortality and declining growth might also increase in relatively humid regions of higher elevation with ongoing warming. This conclusion may be helpful to understand the relationship between tree growth and climate factors under regional climate variability, but this topic also needs to receive more attention and research to explain and test its validity in the future. Moreover, it is important to scientifically monitor the dynamics of tree growth and renewal, effectively manage the forest communities, and accurately predict the development of ecosystems.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (Projects No. 41630750 and 41361010) and Provincial Youth Science and Technology Fund Projects of Gansu Province (1308RJYA054). We especially thank Xiaolong Shang for sampling work in the field. We are grateful to Yiping Zhang, Yan Wen, Wen Xiao and Ao Shen for their assistance in data analysis and laboratory work. We also thank the anonymous referees for helpful comments on the manuscript.

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