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Stability evaluation of radial growth of *Picea schrenkiana* in different age groups in response to climate change in the eastern Tianshan Mountains

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Abstract: Global warming causes an unstable response in tree radial growth at high latitudes in the Northern Hemisphere. Additionally, different climatic responses of different age groups of trees have been found due to their different physiological mechanisms. In this study, the response stability and growth trend of three age groups (young < 100a, middle 100-200a, old ≥ 200a) of *Picea schrenkiana* (Schrenk spruce) to climate change and the causes of the different responses in different age groups were analyzed in the relatively dry climate of the eastern Tianshan Mountains. The results showed that: (1) With the abrupt increase in temperature in 1989, the annual mean minimum temperature became the dominant radial growth-limiting factor of the three age groups of Schrenk spruce. (2) The radial growth of the middle and young groups was more sensitive than that of the old group based on growth-climate correlation analysis. (3) The radial growth of the different age groups had different responses to climate factors, and all age groups were unstable on time scales. (4) The trend of the linear regression simulation of the basal area increment (BAI) indicated that the Schrenk spruce had the same growth trends in different age groups with growth first increased and then decreased; however, the decreased growth rate was higher in the middle and young age groups than in the old age group after the abrupt increase in temperature. Therefore, we should pay active attention to the impact of drought on Schrenk spruce in the eastern Tianshan Mountains and should particularly strengthen the conservation and management of the middle and young age groups.

Keywords: Divergent response; Global warming; Tree age; Annual mean minimum temperature; Schrenk spruce; Tianshan Mountains

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Introduction

Global climate change has had a significant effect on human production activities and forest ecosystems for nearly a century. Forest ecosystem are sensitive to climate change and are characterized by a series of changes in species distribution, forest productivity, biodiversity, carbon balance and the carbon cycle (Cox et al. 2013). Therefore, it is necessary to understand the relationships between climate change and tree growth. Studies on long-term climate change and tree responses to climate are limited due to the short time scale and uneven distribution of instrumental climate data. However, tree rings have been widely used in climate reconstruction and growth-climate relationship studies, as tree rings provide past climate information and have dating accuracy, high resolution, a close relation to climate and wide distribution (Shao 1997; Ewane and Lee 2017).

Traditional dendrochronology thought that the responses of detrended chronologies of different ages to climate factors were consistent, such as *Pinus tabulaeformis* in the Guancen Mountains of China, *Picea abies* in the Austrian Alps, and *Pinus longaeva* in the eastern Italian Alps (Rossi et al. 2008; Schuster and Oberhuber 2013a; Sun et al. 2015). However, there were still age effects and different response results of detrended chronologies to climate due to the different physiological functions of trees of different ages. The sensitivity of *Pinus tabulaeformis* was different in the old and young age groups on the northeastern Qinghai-Tibetan Plateau. The middle and old age groups of *Picea schrenkiana* were more sensitive than the young age group in the eastern Tianshan Mountains, and the younger *Araucaria araucana* in Patagonia, Argentina were more sensitive. There were differences in the response of *Larix gmelinii* to climate factors in Northeast China (Zhang et al. 2003; Wang et al. 2009; Hadad et al. 2015). Studies on tree physiology have proven that the response mechanism of trees of different ages to climate is not consistent with differences in photosynthetic and respiratory intensity, hydraulic conductivity, nutrient absorption and storage of trees of different ages; thus, age might affect the response sensitivity of trees to climate factors (Joana et al. 2009).

Tree rings are influenced by their own genetic factors as well as by external environmental factors. Since 1990s, the response relationship between the radial growth of trees and climate factors has changed, and the trends of tree-ring width do not increase or decrease with temperature in high latitude and altitude regions in the Northern Hemisphere (40° N-60° N). And the sensitivity of tree to climate response decreases after warming was defined as "divergence problem" (D'Arrigo et al. 2008). With the development of research, different responses of tree growth to climate have been found in different areas in different tree species, such as *Larix sibirica* in the Tianshan Mountains, *Pinus koraiensis* in the Changbai Mountains, and *Abies faxoniana* in the western Sichuan Mountains (Li et al. 2012; Yu et al. 2013; Jiao et al. 2015). Meanwhile, the divergence problem challenges the scientificity and rationality of traditional dendrochronology research based on the principle of "uniformity", such as the growth-climate relationship and historical climate reconstruction. There is no consensus on the causes and mechanisms of the divergence problem, including the tail effect of detrends, temperature threshold, nonlinear response of trees to climate, and age effect (Cooker and Peters 1997; D'Arrigo et al. 2004). Trees of different ages may have different climate sensitivities, which will have an impact on the responses of tree growth to climate (Gai et al. 2017). Therefore, it is necessary to systematically analyze the age effect on the responses of tree growth to climate in additional regions and tree species.

The Tianshan Mountains are an ideal area for studying the temporal stability of tree radial growth in trees of different ages caused by their varied topography and complex climatic conditions. Compared with the western and central areas, there is less precipitation and tardier in the eastern Tianshan Mountains (Li 1991), where trees are subjected to more restrictive factors and are more sensitive to climate factors. In addition, the climate has changed from warm-dry to warm-wet since the 1960s in the Tianshan Mountains (Yao et al. 2018), which provides an ideal opportunity to study whether tree responses and growth trends change in response to climate transformation. At present, a large number of studies have been carried out in the Tianshan Mountains, especially in the western and central. But researches were mainly focused on the historical climatic reconstruction. For example, June-August mean temperature was reconstructed since 1850 C.E. in the western Tianshan Mountains, 256-year total precipitation from June of previous year to May of current year was reconstructed in central Asia, standardized precipitation evapotranspiration index (SPEI) in August-July was reconstructed in eastern Tianshan from 1725 to 2013, Palmer drought severity index (PDSI) April-May in was reconstructed in central Tianshan Mountains over the past 553 years (Chen et al.

2014; Chen et al. 2016; Jiang et al. 2016; Zhang et al. 2017; Zhang et al. 2019a; Zhang et al. 2020). And some researches on the response of trees to climate factors were analyzed, showing the growth of Schrenk spruce was the mainly controlled by the minimum te mperature in eastern Tianshan Mountains, and precipitation was the main limiting factor for radial growth of Schrenk spruce in the central Tianshan Mountains (Jiao et al. 2015; Jiao et al. 2016; Zhang et al. 2016; Wu et al. 2018; Zhang et al. 2019b). In addition, some studies have found that altitude and tree species could affect the response stability of radial growth of trees to climate change (Huo et al. 2017; Jiao et al. 2019).

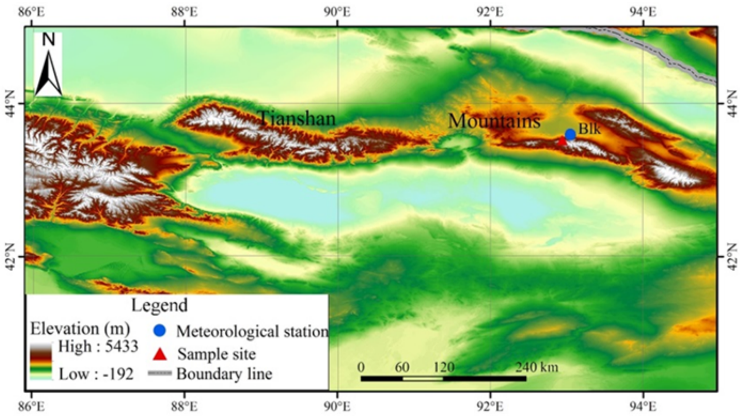

Figure 1 Location of the study region and the nearest meteorological station on the north slope of the eastern Tianshan Mountains.

However, there was a lack of evaluation on the response stability of the tree-age effect. Therefore, we analyzed the dynamic r elationship of growth-climate and radial growth patterns to determine the climate sensitivity of different age groups of Schrenk spruce in the eastern Tianshan Mountains. This article investigates the following: (1) Analysis of the main controlling climate factors of different age groups; (2) identification of age group that is most sensitive to climate change; (3) assessment of the response stability of different age groups to climate factors; and (4) characterization of the trends of radial growth in different age groups in response to climate transformation.

1 Materials and Methods

1.1 Study area

The Tianshan Mountains are an international mountain range located in the central part of the Eurasian continent, with a total length of 2500 km and a territorial length of approximately 1700 km in Xinjiang Province of China. The study region (43°32.1' N, 92°56.3' E) is located on the north slope of the eastern Tianshan Mountains with an altitude of 2552 m, which belongs to the temperate continental semi-arid climate area and has the same period of water and heat (Figure 1). Water vapor from the Atlantic Ocean enters the Xinjiang region under the influence of the westerly circulation of central Asia, showing that the amount of precipitation in the western Tianshan Mountains is higher than that in the eastern Tianshan Mountains because of the barrier provided by the Tianshan Mountains (Li 1991). The annual mean temperature was 2.08°C, and the annual total precipitation was 220.64 mm during 1960-2012. The maximum temperature was 18.08°C in July, and the lowest temperature was -17.63°C in January. The precipitation in the growing season (from May to September) accounted for 74% of the annual precipitation (Figure 2a). Meanwhile, the temperature (mean minimum temperature, mean temperature and mean maximum temperature) increased significantly ($P<0.01$), while the annual total precipitation increased slightly ($P>0.05$). According to the Mann-Kendall test (Goossens and Berger 1987), 1989 was a year in which the mean temperature changed abruptly, but there was no year with an abrupt change in annual total precipitation (Figure 3a, b). The mean minimum temperature, mean temperature, mean maximum temperature and total precipitation in 1989-2012 were 2.91°C, 1.98°C, 0.87°C and 23.04 mm higher than those in 1960-1988, respectively (Figure 3c, d, e, f).

1.2 Sample collection and chronology establishment

The sampling point was selected in Barkol of the eastern Tianshan Mountains, the sampling time was August 2013. To minimize the impact of sample differences on the results, we chose the

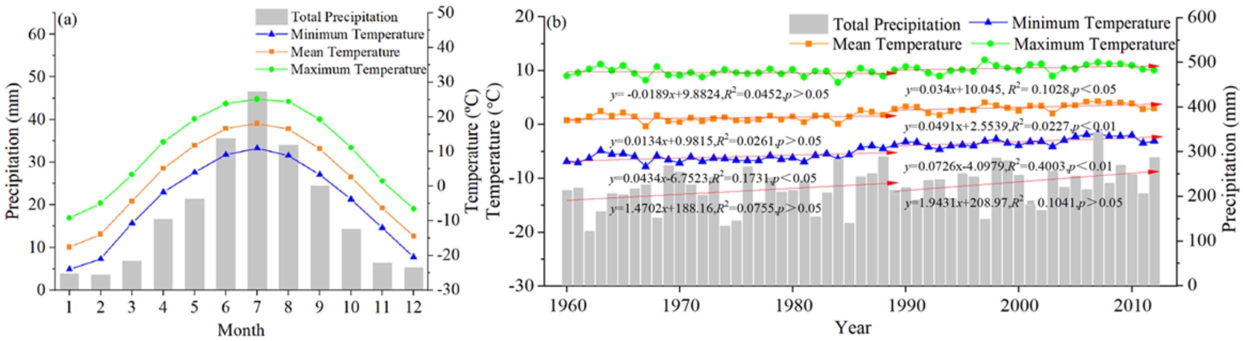

Figure 2 Monthly (a) and interannual (b) variability of minimum temperature, mean temperature, maximum temperature and total precipitation from 1960 to 2012 on the north slope of the eastern Tianshan Mountains (the red solid lines with arrows represent the trends simulated by linear regression).

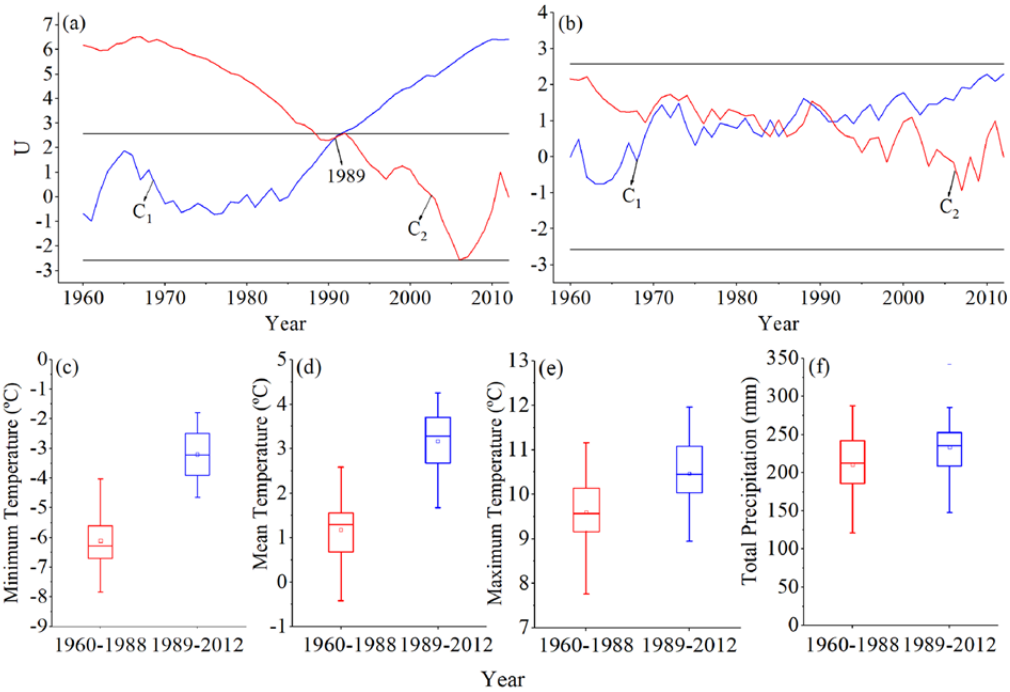

Figure 3 Mann–Kendall test results of annual mean temperature (a) and total precipitation (b), and climatic elements of minimum temperature (c), mean temperature (d), maximum temperature (f) and total precipitation (f) boxplots during the two periods of 1960–1988 and 1989–2012 (C1 represents the U values for the normal time series, C2 represents the U values for the retrograde time series, and the solid lines indicate the value of significance at the 0.01 level).

same geographical conditions for sampling, with a north slope of 27°, mean canopy density of 30%, mean tree spacing of 3.0 m, and mean crown width of 2.7 m. Trees with good growth conditions and no obvious effects of fire , pests and diseases were selected as samples. Two cores per tree were extracted at a breast height of 1.3 m with a 5.15-mm-diameter increment borer along both the slope direction and the vertical slope direction, and a total of 86 tree cores were obtained from 43 trees.

In the laboratory, the obtained tree cores were placed in a wooden bracket. After the tree cores were air-dried, they were polished with 120, 400 and 600 grit until a clear tree-ring boundary could be seen. The tree-ring width of each sample core was measured by a LINTAB measurement system (TM6, Rinntech, Heidelberg, Germany) with an accuracy of 0.001 mm. To ensure the accuracy of the dating and measurement results, COFECHA software (Holmes 1983) was used to cross-date the measurement results. According to the relationship between the physiological characteristics of Schrenk spruce (Carrer and Urbinati 2004), the tree cores were divided into three age groups: young age with <100 a (mean age 69a), middle age with 100-200a (mean age 122a), and old age with >200a (mean age 236a). The trend of measuring the tree-ring width sequence was removed by using a negative exponential curve or linear regression method using ARSTAN (Fritts 1976). The standard chronologies (STDs) of the three age groups of Schrenk spruce were obtained to analyze the dynamic growth-climate relationship.

The statistical characteristic parameters were calculated to assess the reliability and quality of the chronologies of the three age groups (Table 1). The mean sensitivity and standard deviation of the three chronologies were all greater than 0.20, indicating that the interannual variation and fluctuation range of tree-ring width of the three age samples were relatively large. The mean within-tree correlations of chronologies in the young, middle and old age groups were 0.733, 0.718 and 0.758, respectively, indicating that the variations in the tree-ring width of the three age groups were basically consistent. The signal-to-noise ratios in the middle and young age groups (29.668 and 25.776, respectively) were higher than those in the old age group (21.734), indicating that the chronology in the middle and young age groups contained more climate information and they were more susceptible to climate impacts. The values of the expressed population signal (EPS) for the three chronologies were larger than 0.85, indicating the higher quality and reliability of chronologies, which were suitable for research on the relationship between radial growth and climate factors.

Table 1 Dendrochronological characteristics of chronologies in the three age groups of Schrenk spruce on the north slope of the eastern Tianshan Mountains (YAC: young age chronology, MAC: middle age chronology, OAC: old age chronology).

Dendrochronological Parameters	YAC	MAC	OAC
Number of cores / trees (*N*)	24/12	34/17	28/14
Time span (a; EPS>0.85)	1914-2012	1823-2012	1735-2012
Mean tree age (a)	69	122	236
Mean sensitivity (MS)	0.249	0.256	0.261
Standard deviation (SD)	0.204	0.232	0.235
Autocorrelation coefficient (AC)	-0.140	-0.052	-0.059
Correlation Coefficient (*R*)	0.419	0.533	0.608
Mean correlation in a tree (*R*1)	0.733	0.718	0.758
Mean correlation between trees (*R*2)	0.367	0.525	0.596
Signal-to-noise ratio (SNR)	25.776	29.668	21.734
Expressing population signal (EPS)	0.852	0.967	0.956

1.3 Meteorological data

The meteorological data were acquired from the Barkol meteorological station, which was the nearest to the sampling points (93.03°E, 43.36°N; altitude: 1677.3 m), and the data included the monthly minimum temperature, mean temperature and maximum temperature and the monthly total precipitation. The drought index of the SPEI was calculated, integrating the temperature, precipitation, solar radiation, wind speed, and water vapor pressure factors (Vicente et al. 2010). Climate factors from May of the previous year to September of the current year during the timespan from 1959 to 2012 were selected for analysis because of the "lag effect" on the response of radial growth to climate.

1.4 Statistical analysis

The main climate factors limiting the radial growth of trees were determined by calculating the Pearson correlation coefficient between the chronologies of different age groups and climate factors. The dynamic variations in the tree growth-climate relationships were analyzed by moving correlation backward from the fixed year 1960 to the moving interval of 24 years using the DendroClim2002 program (Biondi and Waikul 2004). The basal area increase (BAI) of Schrenk spruce was calculated using raw tree-ring width chronologies to determine the radial growth trend under climate change. The BAI is a much more biologically meaningful variable used to quantify tree growth patterns because it inevitably overcomes the deviation of data transformation (Rubino and McCarthy 2000; Go´mez-Guerrero et al. 2013). In particular, the downward trend of BAI indicated that the radial growth of trees was inhibited by environmental pressure (Xu et al. 2014a). The BAI calculation formula is as follows:

$$\mathrm{BAI_t} = \mathrm{BA}_t - \mathrm{BA}_{t-1} = \pi((R_{t-1} + \mathrm{TRW}_t)^2 - (R_{t-1})^2) \quad (1)$$

where BA represents the basal area of a continuous cross-section, *R* is the tree-ring length measured from pith to year *t-1*, and TRW is the raw width of the tree-rings measured in year *t*.

2 Results and Analysis

2.1 Correlation between chronologies of three age groups and climate factors

The relationships between the radial growth of the three age groups and climate factors before and after the abrupt temperature transition were analyzed (Figure 4). From 1960 to 1988, the chronology of young trees was significantly positively correlated with the minimum temperature in May, June and October of the previous year and significantly positively correlated with the SPEI in November of the previous year

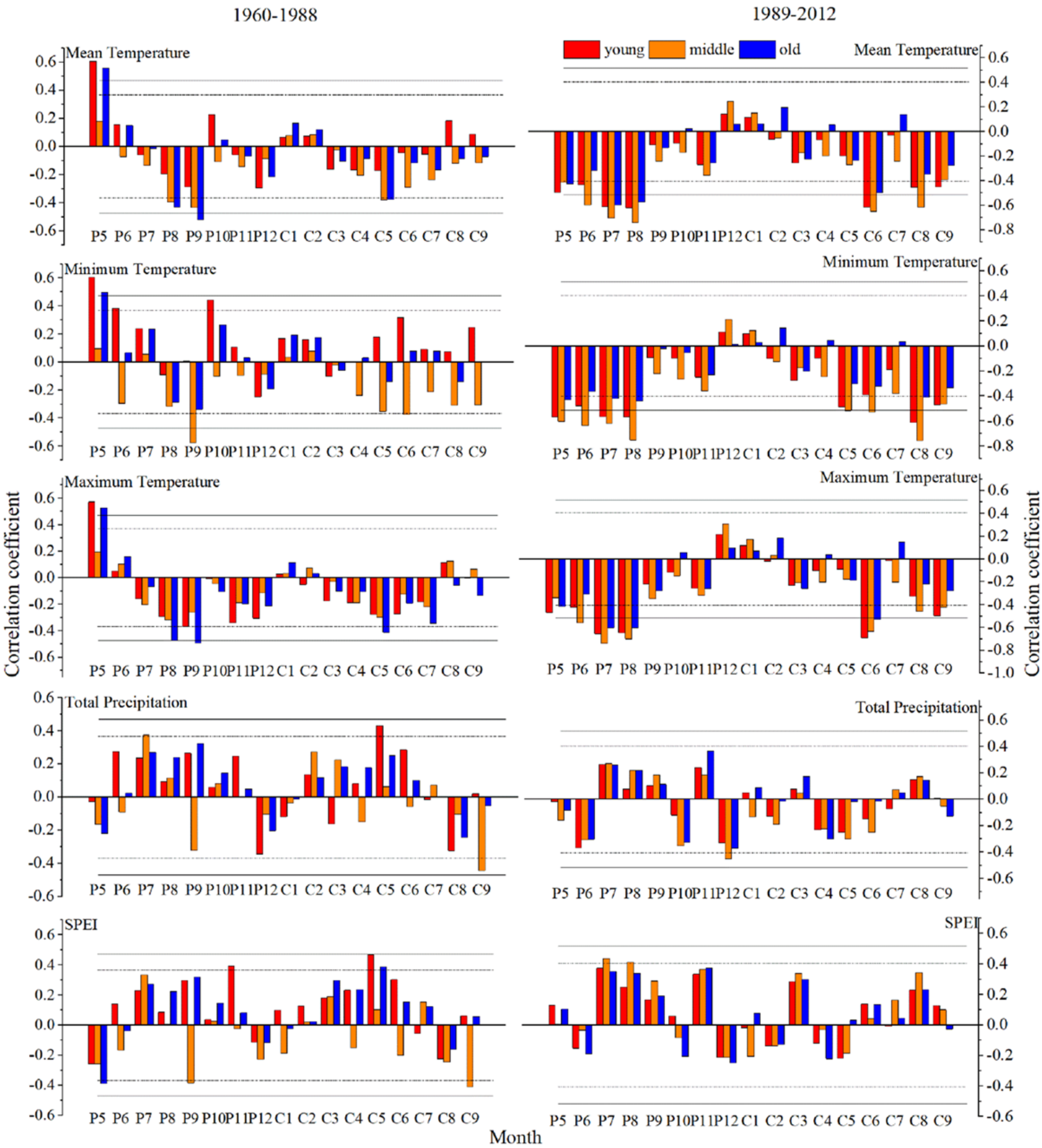

Figure 4 Correlations between chronologies and monthly climate factors during 1960–1988 and 1989–2012 (the dotted lines represent significance at the 0.05 level, and the solid lines represent significance at the 0.01 level. P: previous year, C: current year, P5: May of previous year, C1 January of current year).

and in May of the current year ($P<0.05$). The chronology of middle trees had a significant negative correlation with the minimum temperature in September of the previous year and in June of the current year and was significantly negatively correlated with the SPEI in September of the previous year and in September of the current year ($P<0.05$). The chronology of old trees was significantly positively correlated with the minimum temperature in May of the previous year ($r=0.497$, $P<0.01$), significantly positively correlated ($r=0.386$) with the SPEI in May of the current year and significantly negatively correlated ($r=-0.388$, $P<0.01$) with the SPEI in May of the previous year.

From 1989 to 2012, the chronology of young trees had a significant negative correlation with the minimum temperature in May to August of the previous year and in May, August and September of the current year ($P<0.05$). The chronology of middle trees had a significant negative correlation with the minimum temperature in May to August of the previous year and in May, June, August and September of the previous year and a significant positive correlation with the SPEI in July and August of the previous year ($P<0.05$). The chronology of old trees had a significant negative correlation with the minimum temperature in May, July, and August of the previous year and in August of the current year ($P<0.05$). The changes in annual mean temperature, annual maximum temperature and annual minimum temperature before and after the abrupt changes were approximately the same.

Figure 5 showed the results of the first-order difference correlation. From 1960 to 1988, the chronologies of all age groups had the significant positive correlations with mean minimum temperature in May of the previous year ($P<0.05$), and the significant negative correlations in September, December of the previous year and May of current year ($P<0.05$). From 1989 to 2012, the chronology of young trees had the significant negative correlations with mean minimum temperature in May, July of the previous year and May, June, September of the current year ($P<0.05$), and the significant positive correlation in September of the previous year ($P<0.05$). The chronology of middle trees had the significant negative correlations with mean minimum temperature in May, July, November of the previous year and May, June, August, September of the current year ($P<0.05$). The chronology of old trees had the significant negative correlations with mean minimum temperature in July of the previous year and May of the current year ($P<0.05$).

2.2 Moving correlation between chronologies of three age groups and climate factors

The results of Pearson correlation between the radial growth and climate factors in two time periods (1960-1988 and 1989-2012) showed that the mean minimum temperature in the growing season were the main limiting factors of tree growth for the three age groups (Figure 4). And warming can lead to the aggravation of water deficit. Therefore, moving correlations between the chronologies of the three age groups and the minimum temperature and SPEI were conducted.

The chronologies of the three age groups showed a trend from a positive correlation to a negative correlation, or the negative correlation gradually increased with the mean minimum temperature from May to August in the previous growing season and from May to September in the current growing season. However, the positive correlation between the chronologies of the three age groups and the mean minimum temperature in September of the previous year was strengthening. The transition from positive to negative responses of the middle and young trees occurred earlier than that of the old trees (Figure 6).

All three age groups chronologies showed a trend from negative correlation to positive correlation or a gradually increasing positive correlation with the SPEI in May, July and August of the previous year and in August and September of the current year; additionally, all three showed a trend from positive correlation to negative correlation or a negative correlation that gradually increased with the SPEI of the growth season in May of the current year. There were also significant differences in the sequences of the three age groups. For the samples in the middle age group, the positive correlation with the SPEI decreased only in May of the current year during the growing season and increased in the other growing months. For the young and old age groups, a decreasing

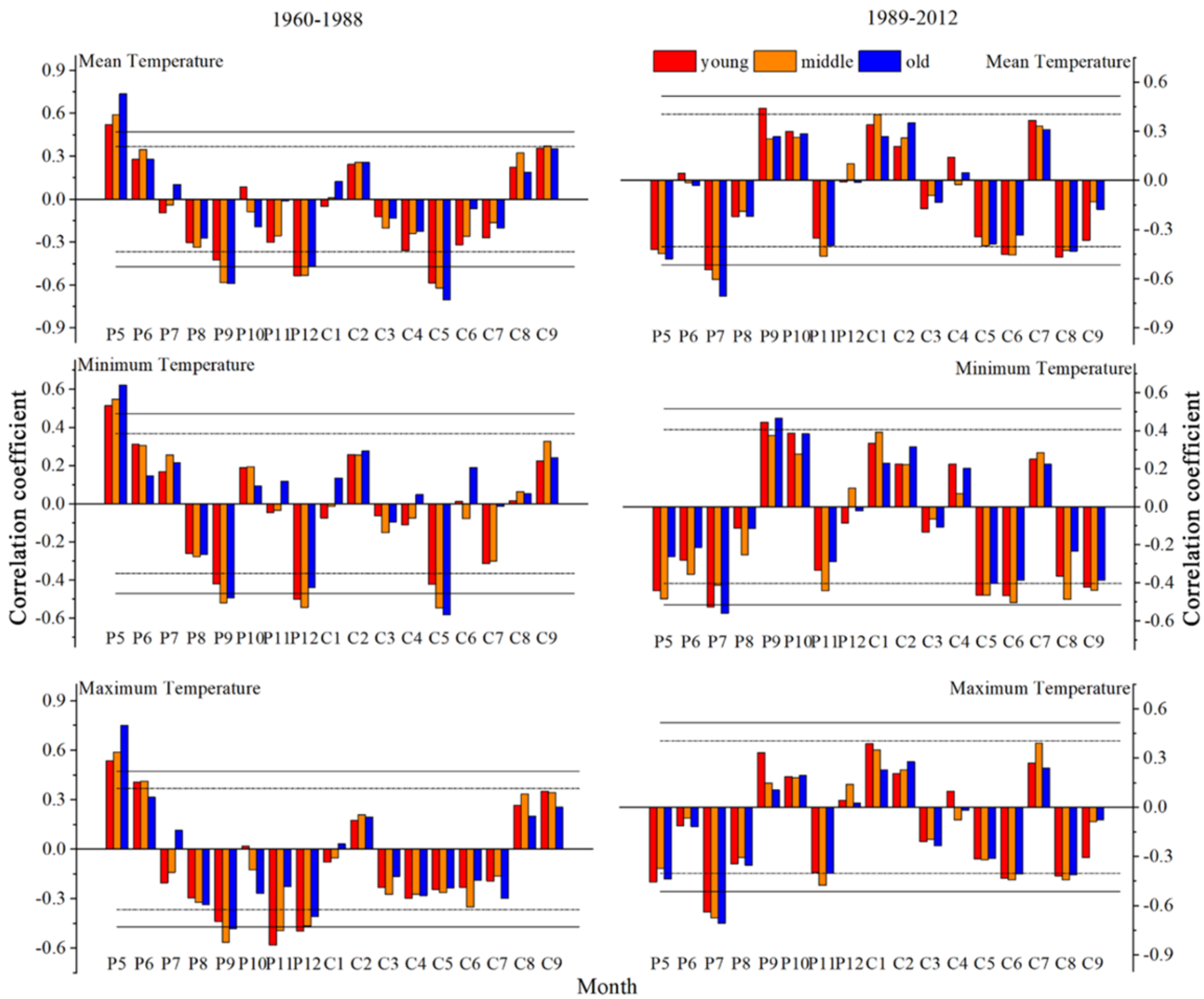

Figure 5 First-order difference correlations between chronologies and monthly climate factors during 1960–1988 and 1989–2012 (the dotted lines represent significance at the 0.05 level, and the solid lines represent significance at the 0.01 level. P: previous year, C: current year, P5: May of previous year, C1 January of current year).

trend with the SPEI was observed in June and September of the previous growth season, which was different from the middle age group. There was also a certain difference between the old and young age groups, and the results showed that the positive correlation between the old group and the SPEI of the growing season in June and July of the current year was weakened, while the positive correlation between the young group and the SPEI of the growing season in July of the current year was enhanced. The three age groups showed a stable and significant positive correlation with the SPEI in July of the previous year (P<0.05), and the old group also showed a stable and significant positive correlation with the SPEI in August of the previous year (P<0.05). For the combination of the SPEI in May-August of the previous year and in August-September of the current year, all three age groups showed a trend from negative correlation to positive correlation or a gradually increasing positive correlation.

2.3 Growth trend of three age groups

Radial growth of the three age groups showed a trend of first increasing and then decreasing based on the 10-year moving average of the BAI (Figure 7). However, the three age groups showed different trends after the abrupt temperature transition. On the one hand, the decreasing trend of BAI for the middle age group in 1997 was earlier than that for the young and old groups in 2000. On the other hand, the decreasing BAI rates for the middle age group (3 $cm^2/10a$) and the young age

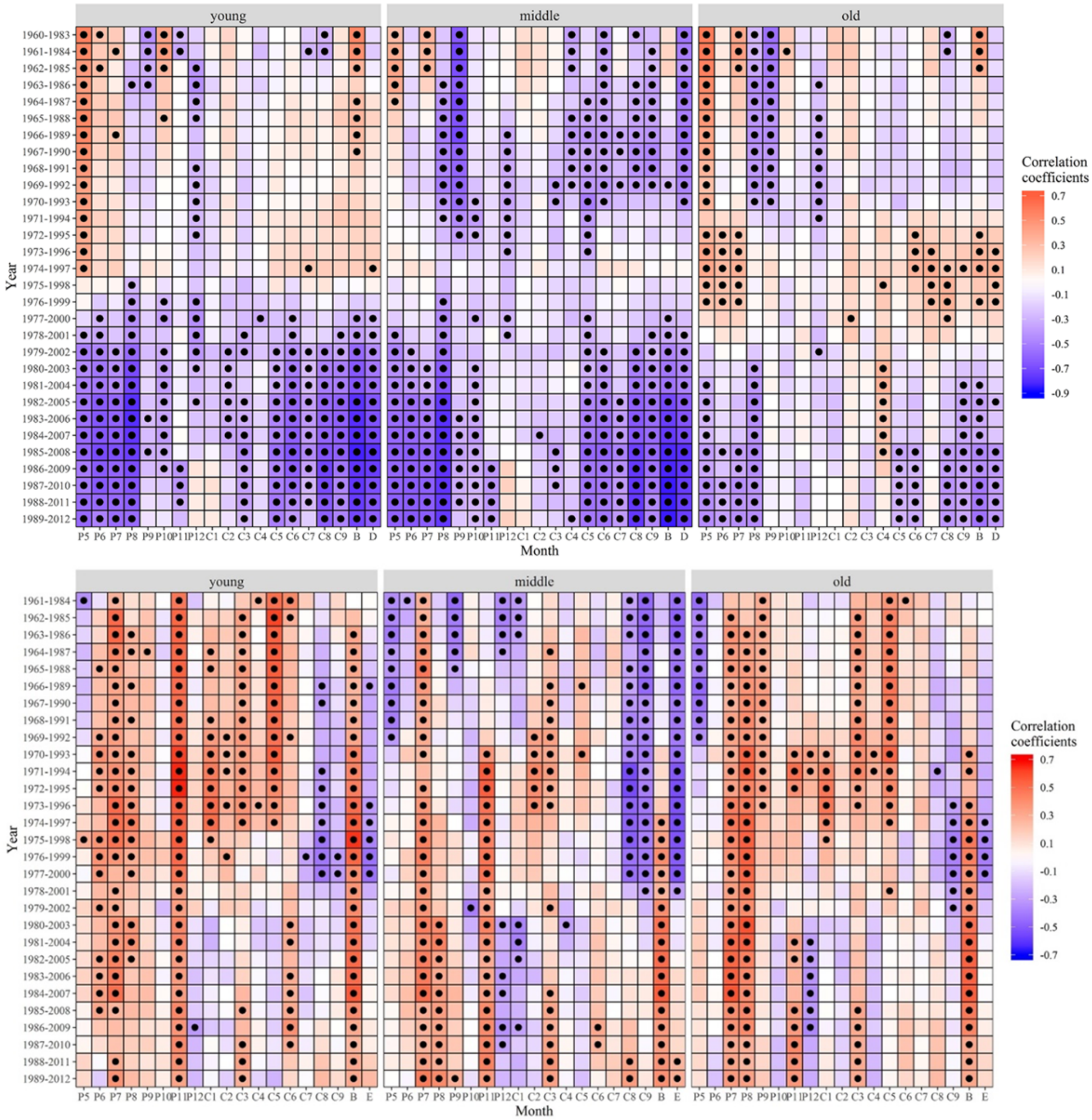

Figure 6 Moving correlation results between chronologies and minimum temperature (a) and standardized precipitation evapotranspiration index (SPEI) (b) Moving window: 24 years. The black solid dots represent significance at the 0.05 level. Red represents a positive correlation, and purple represents a negative correlation. (B: the combination of May and August of the previous year, D: the combination of May to September of the current year, E: the combination of August to September of the current year, P: previous year, C: current year, P5: May of previous year, C1 January of current year).

group (1.5 $cm^2/10a$) were higher than that for the old age group (0.7 $cm^2/10a$).

3 Discussion

3.1 Main controlling climate factors of different age groups of Schrenk spruce

The main limiting climate factors of different age groups were consistent before and after the abrupt change in temperature, they were both subject to temperature restriction not precipitation (Figure 4). The research regions are located in the high-altitude area of the eastern Tianshan Mountains, where precipitation is relatively high than low-altitude (the total precipitation in the growing season before the abrupt change of temperature was 31.15 mm and 35.12 mm after abrupt change of temperature) and temperature is relatively low (the mean temperature in the growing season was 13.92°C before the abrupt change of temperature and 15.78°C after the abrupt change of temperature). Therefore, the radial growth of trees in high-altitude regions was more affected by temperature (White et al. 2014; Malanson 2017). BAI of different age groups all showed the trends of first increase and then decrease (Figure 7). We found that the correlation was mainly significantly positive between tree radial growth and temperature from 1960s to 1970s, not significant from 1970s to 1980s, and significantly negative from 1989 to 2012. According to the temperature threshold theory, when the temperature is higher than the lowest threshold value of tree, the increase in temperature is beneficial to tree growth due to increasing photosynthesis, delaying the growth season and prolonging the cell differentiation time, reducing the negative effects of low temperature on plants, but when the temperature continues to increase beyond the optimum threshold value of trees, the radial growth of tree is restricted by the increase in temperature due to enhanced respiratory consumption and drought stress (Jacoby et al. 1981; D'Arrigo et al. 2009; Jiang et al. 2014; Zhang et al. 2018). Both the temperature and the precipitation in the research region increased, but the range of increased temperature was higher than that of precipitation (Figure 2b, Figure 3). Climate warming in recent decades has changed the climate factors limiting the radial growth of trees and the stability of the tree growth-climate relationship in the eastern Tianshan Mountains (Figure 4).

The correlation changes between the three chronologies and temperature were basically the same before and after 1989. By comparing the minimum temperature, the mean temperature and the maximum temperature, our results showed that the three chronologies were most sensitive to the minimum temperature (Figure 4). Therefore, the minimum temperature was the main controlling factor of Schrenk spruce in recent decades. The same conclusion was found in the middle and eastern Tianshan Mountains and in the Qilian Mountains (Gao et al. 2013; Xu et al. 2014a; Jiao et al. 2015). Although the temperature increased significantly after 1989, the rate of increase of the mean minimum temperature (0.955±0.075°C/10a, P<0.01) was significantly higher than that of the maximum temperature (0.245±0.071°C/decade, P<0.01). The minimum temperature increase significantly increased tree dark respiration and reduced the net accumulation of photosynthetic nutrients, restricting the radial growth of trees and forming narrow tree rings (Peng et al. 2013; Franceschini et al. 2013; Palombo et al. 2014; Zhang et al. 2015). In addition, the significant increase in minimum temperature could have increased soil moisture evaporation and drought stress, which led to the decline of radial growth (Peng et al. 2005; Rozas et al. 2008; Wu et al. 2013; Qi et al. 2015).

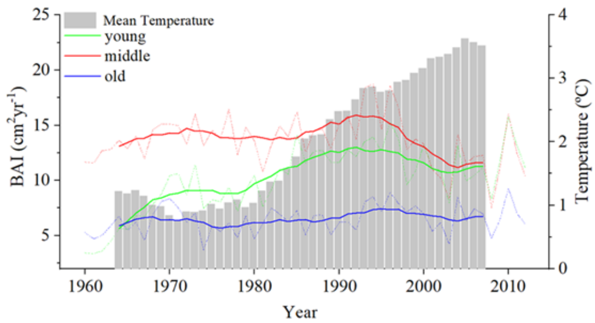

Figure 7 Trend of the basal area increment (BAI) for Schrenk spruce in the whole time series (a) and during 1960–2012 (b) The solid line represents the 10-year moving average of BAI and the dotted line represents the individual BAI of tree age groups.

3.2 Sensitivity of different age groups of Schrenk spruce to climate change

The sensitivity difference among the three age groups after 1989 was more significant than that before the abrupt transition, showing the increasing correlation of the month number and the significant degree between chronology and climatic factors. Meanwhile, the middle and young age groups of Schrenk spruce were more sensitive to climate change than the old age group (Figure 4). In other studies in the Tianshan mountains, the middle and old age trees of Schrenk spruce is more sensitive than young trees to climate, and it might have something to do with the regional environmental differences (Jiao et al. 2017). For example, the correlation coefficients of radial growth in the middle and young age groups with temperature (minimum, mean and maximum temperature) in the growing season were higher than those in the old age group basically. The moving correlation analysis of the chronologies and the minimum temperature also showed that the middle and young age groups had earlier divergent responses than the old age group (Figure 6a). Moreover, the decline rate of BAI in the middle and young age groups was faster than that in the old age group according to the BAI 10-year moving averages under climate change (Figure 7). Research on *Picea glauca* in Canada, *Juniperus thurifera* in north-central Spain, *Pinus pinaster* on the northwest coast of Portugal, and Schrenk spruce in the western and eastern Tianshan Mountains also provided evidence that older trees were less sensitive to climate change (Szeicz and MacDonald 1994; Rozas et al. 2009; Vieira et al. 2009; Wu et al. 2013).

The reason for the sensitivity difference among trees of different ages might relate to differences in the resource acquisition ability and consumption of different age groups under the condition of increased environmental stress. Compared with old trees, the middle and young trees were less competitive in obtaining water and nutrient resources due to imperfect roots and channeling tissues (Pichler and Oberhuber 2007). In addition, the middle and young trees had higher nutrient consumption than old trees because stomatal conductance showed a downward trend as tree age increased, and higher stomatal conductance could increase the transpiration intensity and the consumption of nutrients. In addition, delayed cambium cell growth significantly reduced the sensitivity of the old age group (Rossi et al. 2008; Bond 2000; Richard et al. 2017). With global warming, drought stress has become the main threat limiting forest ecosystems in the inland mountains of Asia. Our results confirmed this conclusion, supporting evidence of the enhanced negative correlation of radial growth with minimum temperature and the positive correlation of radial growth with the SPEI (Figure 6b). Meanwhile, the older trees were more drought-tolerant than the middle and young groups, showing less sensitivity to drought stress (Ogle et al. 2000). A number of studies have also found that older tree groups are more tolerant to drought, such as *Pinus edulis* in the northern United States, *Picea schrenkiana* in the eastern Tianshan Mountains, *Pinus cooperi* in the Sierra Madre Occidental and *Pinus taiwanensis* in Taiwan (Ruiz-Benito et al. 2015; Pompa and Hadad 2016; Jiao et al. 2017).

3.3 Influence of age-effect on unstable growth-climate relationships

Schrenk spruce in the eastern Tianshan Mountains had unstable growth-climate relationships based on a comparison of the differences in correlation coefficients between chronology and climate factors before and after temperature change and the moving correlation analysis (Figures 4, 5), e.g., the divergence responses of the three age groups with minimum temperature in the growing season from May to August of the previous year and in May, June, August and September of the current year (Figure 4). The radial growth divergent response to temperature is mainly caused by the drought stress, which can accelerate soil water evaporation and enhanced respiratory consumption (Liang et al. 2006; Oberhuber et al. 2008). The water restriction was aggravated after 1989 in the study region, with the temperature increasing significantly ($P<0.01$) and the total precipitation remaining relatively stable ($P>0.05$) in terms of interannual variation (Figure 4). In addition, the sampling site is relatively steep (slope of 27°), with high solar radiation and soil permeability, exacerbating the effects of drought stress on trees (Xu et al. 2014b). We believe that the reason for the different responses of tree growth to the climate in Schrenk spruce are enhanced respiratory consumption and water stress caused by increasing temperature.

There was no divergent response of radial growth in the three age groups in some months, showing a stable significant negative correlation with the mean minimum temperature in August of the previous year ($P<0.05$) and a significant positive correlation with the SPEI in July of the previous year ($P<0.05$). These months without divergence can be used for historical climate reconstruction accordingly.

Tree age would have an impact on the different responses of tree growth to climate (Gai et al. 2017).

Our results showed that there were differences in the divergence month and the starting time of divergence among the three age groups. For example, the middle trees had divergent responses to minimum temperature in all months of the growing season, the young trees had responses from May to August in the previous growing season and from May to September in the current growing season, and old trees had responses from May to September in the previous growing season and in May, June, August and September of the current growing season. In addition, as climate warming progressed, the divergence between the middle and young age groups in the temperature of the growing season began in the 1970s, but the old age group started relatively late, around the 1980s and 1990s (Figure 6). The difference in tree divergence response at different ages is related to tree sensitivity to climate change. The middle and young age groups were more sensitive to climate factors than the old age group and were more prone to create different responses of tree growth to climate. The old trees had obvious advantages in obtaining resources, reducing resource consumption and mitigating drought stress, which allowed them to maintain stable growth under climate change (Figure 7). Therefore, it is necessary to classify trees by age with different physiological processes to improve the research accuracy of the growth-climate dynamic relationship with climatic warming. Meanwhile, the management and protection of middle and young trees should be strengthened according to the response discrepancies of different age groups to climate change.

Trees in arid areas are more vulnerable to climate change and less resistant to drought (Schuster and Oberhuber 2013b). The different responses of the three age groups to climate change may explain the influence of water restriction on radial growth caused by climate warming in the Tianshan Mountains. The trees in the eastern Tianshan Mountains were more likely to be affected by drought stress than those in the central and western Tianshan Mountains, with less precipitation and higher temperature (Qi et al. 2015). Especially with the abrupt increase in temperature in 1989, the radial growth of the three age groups showed a decreasing trend in the eastern Tianshan Mountains (Figure 7). Climate warming has caused tree death and forest degradation in different arid and semiarid areas of the globe, such as in the southeastern France Mediterranean Mountains, interior Alaska, northern Canada, and boreal North America (Lebourgeois et al. 2012; Girardin et al. 2016; Cahoon et al. 2018; Marchand et al. 2019). Based on the above results, we speculate that climate warming will trigger changes in the radial growth response to climate factors through a threshold mechanism (Jacoby and D'Arrigo 1995). If temperature continues to increase, drought stress may also affect trees growing in relatively wet areas, such as high altitudes and middle-low latitudes. Therefore, we need to pay attention to the growth trends and response change of trees in relatively humid areas under global climate warming.

4 Conclusion

The age effect is a key factor affecting the stability of the growth-climate relationship and radial growth trends under global climate change. Our results showed that the mean minimum temperature was the most important growth limiting factor of Schrenk spruce in the arid eastern Tianshan Mountains. The divergent responses of radial growth at different ages for dominant coniferous species have also been confirmed in the eastern Tianshan Mountains. However, the middle and young trees had more months with divergent responses, earlier times of divergent transitions and faster declining rates of radial growth than the old trees due to greater sensitivity to climate change. To improve the study accuracy on tree growth trend simulation, historical climate reconstruction, and ecological adaptation strategies, it is necessary to evaluate the age effect on the response stability to radial growth of trees, which can help improve scientific management of forest ecosystems, reduce the inhibiting effect of climate change on tree growth, and maintain the stability of forest ecosystems.

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