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ORIGINAL PAPER

Stability assessment of tree ring growth of *Pinus armandii* Franch in response to climate change based on slope directions at the Lubanling in the Funiu Mountains, China

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Abstract Global warming will affect growth strategies and how trees will adapt. To compare the response of tree radial growth to climate warming in different slope directions, samples of *Pinus armandii* Franch were collected and tree-ring chronologies developed on northern and western slopes from the Lubanling in the Funiu Mountains. Correlation analyses showed that two chronologies were mainly limited by temperatures in the previous June–August and the combination of temperatures and moisture in the current May–July. The difference of the climate response to slopes was small but not negligible. Radial growth of the LBL01 site on the northern slope was affected by the combined maximum and minimum temperatures, while that of the LBL02 site was affected by maximum temperatures. With regards to moisture, radial growth of the trees on the north slope was influenced by the relative humidity in the current May–July, while on the western slope, it was affected by the relative humidity in the previous June–August, the current May–July and the precipitation in the current May–July. With the change in climate, the effects of the main limiting factors on growth on different slopes were visible to a certain extent, but the differences in response of trees on different slopes gradually decreased, which might be caused by factors such as different slope directions and the change in diurnal temperature range. These results may provide information for forest protection and ecological construction in this region, and a scientific reference for future climate reconstruction.

Keywords Tree ring width · Lubanling · *Pinus armandii* Franch · Slope direction · Climate response

Introduction

Global warming is having considerable impact on the earth's ecosystems and tree species will alter their growth strategies to adapt (IPCC 2021). Changes in treeing widths can effectively record variations in environmental factors, this has attracted attention from researchers throughout the world. Tree-ring data with records of response to climate changes, high resolution, accurate dating, continuity and wide geographical distribution, are ideal for the study of past climate change (Wu 1990; Shao 1997).

However, there are still uncertainties in the nonlinear relationships between tree rings and climate change (Fang et al. 2014). For example, With the increase in temperature, the tree ring index and temperature sensitivity decreased abnormally in the northern hemisphere, this phenomenon, also known as the "divergence problem" (Briffa et al. 1998; Wilson and Luckman 2002, 2003; Wilmking et al. 2004; D'Arrigo et al. 2008), first proposed and defined by Jacoby and D'Arrigo (1995) and has attracted the attention of numerous dendrological researchers (Jacoby and D'Arrigo 1995; Wilson and Luckman 2002, 2003; Wilmking et al. 2004; D'Arrigo et al. 2008; Li et al. 2010; Gao et al. 2011;

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Yu et al. 2013; Pellizzari et al. 2016; Gai et al. 2017; Guo et al. 2022a). And with the change of climate, the sensitivity of tree-ring index and climate factors response changes significantly, which is called "sensitivity change". At present, "sensitivity change" studies are generally concentrated in the higher latitudes of the Northern Hemisphere, while microgeomorphology controls local temperature and humidity conditions, and is related to "sensitivity change" (Wilmking 2005; Li et al. 2011; Guo et al. 2016; Zhou et al. 2018; Peng et al. 2023).

Slope aspect is an important factor (Wilmking 2005; Benniea et al. 2008; Li et al. 2011; Guo et al. 2016; Zhou et al. 2018) and has significant impact on the tree radial growth (Wu 1990). Previous studies found that tree growth had different limiting climatic factors depending on slope (Zhu et al. 2004; Dang et al. 2007; Liu et al. 2009; Peng et al. 2010; Qin et al. 2016; Cui et al. 2021), and with the increase in temperature, growth on different slopes showed different sensitivities to climate change (Kirchhefer 2000; Leonelli et al. 2009; Guo et al. 2016; Gou et al. 2021). However, under conditions of climate warming, studies of the response of tree radial growth and the stability of the response of different slopes are relatively limited.

In this study, the Funiu Mountains were selected to investigate the response of tree radial growth to climate factors. As the extension of the Qinling Mountains, the Funiu Mountains are located in the central and eastern part of China, part of a fragile ecological zone (Tian et al. 2009) a transition between subtropical and warm temperate zones and sensitive to climate change (Liu et al. 2014; Li et al. 2020). Previous studies on the relationships between radial growth and climate factors in the Funiu Mountains were based on *Pinus armandii* (Shi et al. 2009; Wang et al. 2010, 2016; Peng et al. 2018a, b, 2019; Li et al. 2020) and *Pinus tabuliformis* (Tian et al. 2009; Shi et al. 2012; Wang et al. 2016; Zhao et al. 2019; Yang et al. 2021a; Li et al. 2022). However, *P. armandii* is a unique evergreen species in China, preferring warm and humid climates. It most concentrated and typical in the Qinling Mountains and also one of the main coniferous species in high altitude areas in the Funiu Mountains (Shi et al. 2009; Li et al. 2020). Previous studies found that too little moisture in May and June limited radial growth of *P. armandii* (Wang et al. 2010; Li et al. 2020) and the response of radial growth to climate change was different between *P. armandii* and other species (Wang et al. 2016; Peng et al. 2018b)and at different altitudes (Peng et al. 2019) and ages (Peng et al. 2018a) but there has been no studies on the effects of different slopes on radial growth.

The objectives of this study were to: (1) establish chronologies of radial growth of *P. armandii* on different slope directions; (2) determine and analyze major climate limiting factors affecting growth; and (3) explore the stability of radial growth to climate warming so as to provide a basis for forest protection and management in the Funiu Mountains under climate change.

Materials and methods

Study region

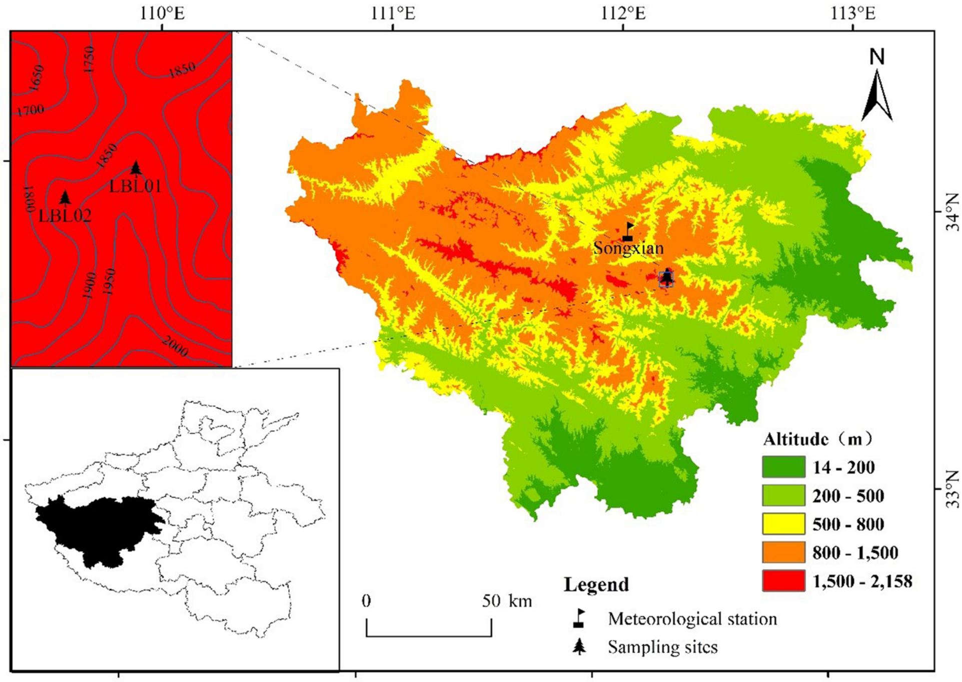
The Lubanling, located in southwest Henan Province of central China, is the highest peak of the Muzhaling Scenic spot in the eastern Funiu Mountains (Fig. 1). It lies in a transitional zone between subtropical and warm-temperate continental monsoon climates (Wang et al. 2010; Li et al. 2020) with abundant rain and distinct seasons. Mean annual temperature is 15 °C, with the coldest in January (1.6 °C), and the warmest in July (27.1 °C); mean annual precipitation is 789 mm, mainly concentrated in July to September (51.5%). *P. armandii* is one of the principle conifer species at high altitudes in the Lubanling (Li et al. 2020). The soil is mainly brown loam and cinnamon soil. At elevations above 1500 m, the predominant soil type is brown loam. Below 1500 m, the north slope is characterized by sandy soil, while the south slope is predominantly cinnamon soil (Yao et al. 2019).

Field sampling and tree-ring data

Two sampling sites were selected on the northern slope (LBL01; 33°43′44″ N, 112°14′37″ E, 1906 m a.s.l.) and the western slope (LBL02; 33°43′40″ N, 112°14′26″ E, 1875 m a.s.l.) of the Lubanling in October 2021. Both sites were less affected by human activity. Following Stokes and Smiley (1968) for the International Tree Ring Bank (ITRDB), samples were mounted, air- dried, and sanded using successively finer grained sandpapers until cells and annual rings were clearly visible. The samples were measured with a Velmex measuring system with 0.001 mm precision. The quality of cross-dating was carefully checked by the COFECHA program (Holmes 1983) and TSAP Win software to ensure accurate dating; cores failing to pass this check were excluded from the raw ring-width series.

The program ARSTAN (Cook and Holmes 1986) was employed to standardize the ring-width series and to detrend biological age affects. A linear function or negative exponential function was first used to detrend tree growth, and then the double weighted average method was used to correct the growth amount. Standard chronology (STD), residual chronology (RES) and arstan chronology (ARS) of sites LBL01 and LBL02 were formed. The RES statistics and the correlation between the RES and climate factors were higher than the STD, and the RES was chosen (Fig. 2).

Fig. 1 Sampling sites and meteorological station in study area



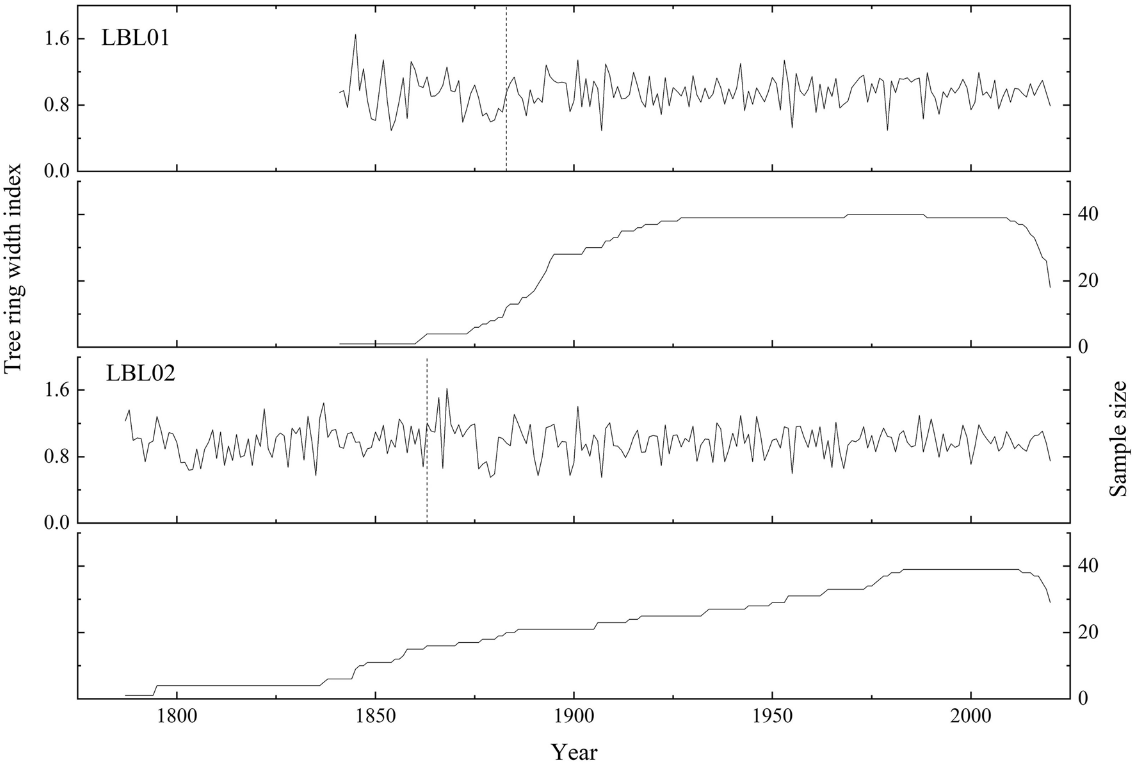


Fig. 2 Tree ring-width chronologies and sample depth from LBL01and LBL02 sites (vertical dash line is the starting year of SSS > 0.85)

Meteorological data

The Songxian (33° 53′ N, 112° 04′ E, 350 m a.s.l.) meteorological station (data for 1963–2018 from the China Meteorological Data Service Center, http://data.cma.cn/) was selected for the sampling sites. The study area features a typical continental monsoon climate with high temperatures and summer rainfall, as observed in the Songxian meteorological records (Fig. 3). Climate factors used in this study include monthly mean maximum temperatures (T_{max}), mean temperatures (T_{mean}), mean minimum temperatures (T_{min}), total precipitation (Pre), mean relative humidity (RH) and diurnal temperature range ($DTR = T_{max} - T_{min}$).

As shown in Fig. 3, since 1963, the T_{max}, T_{mean} and T_{min} in this region have each shown a rising trend, increasing at a rate of 0.2 °C per decade, 0.2 °C per decade and 0.4 °C per decade, respectively. Annual precipitation decreased at a rate of 3.1 mm per decade, but not a significant amount. Annual mean relative humidity decreased at a rate of 0.7% per decade.

Study methods

DendroClim2002 (Biondi and Waikul 2004) performed the correlation analyses between all chronologies and climate factors from the previous March to the current November. The correlation analyses between regional climate factors and chronologies of the LBL01and LBL02 sites were carried out to compare the differences in growth response to climate factors in different slope directions. It was also used to analyze the relationship between radial growth and climate factors through Moving Intervals (a 30-year-period), and to determine the stability of this relationship; the DTR was used to explain the cause of the "sensitivity change" (Jacoby and D'Arrigo 1995; Wilmking 2005; Gai et al. 2017).

Results

Characteristics of tree-ring chronologies

The statistical characteristic values of the RES are shown in Table 1. In order to estimate the quality of all chronologies,

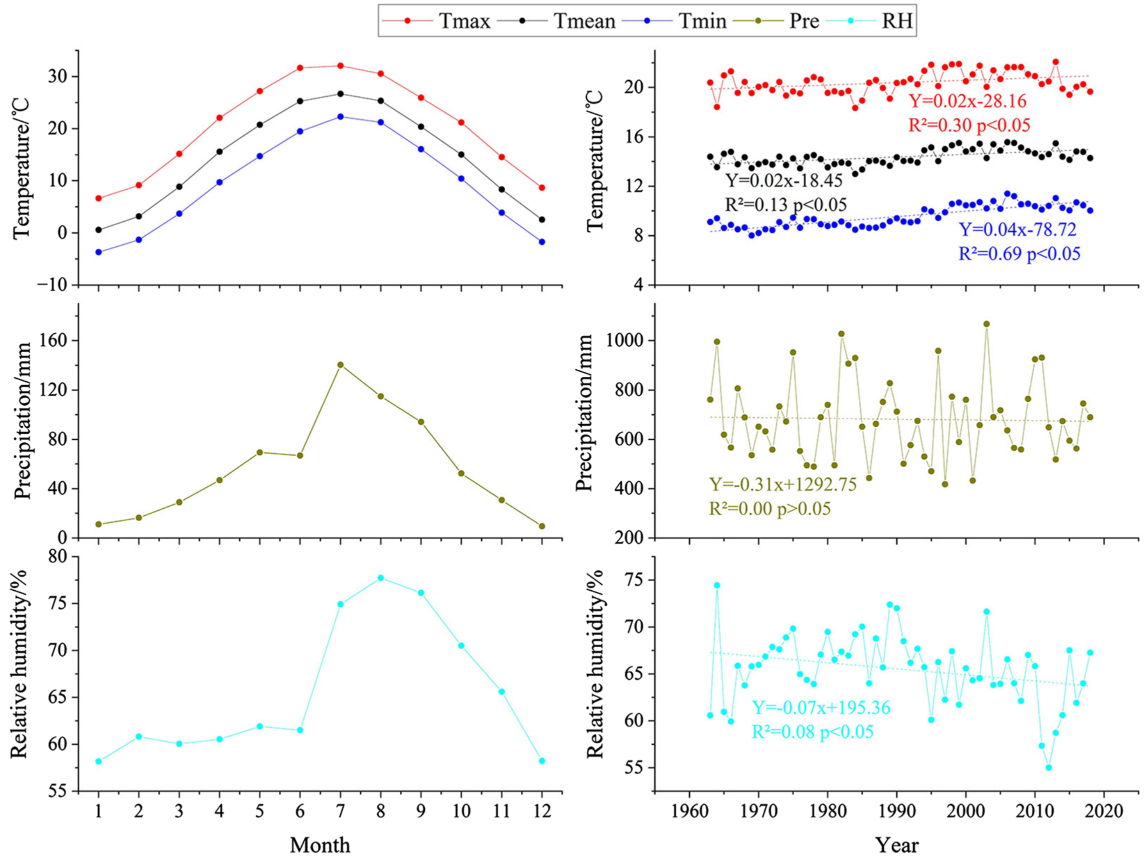


Fig. 3 Monthly mean maximum temperature (T_{max}), monthly mean temperature (T_{mean}), monthly mean minimum temperature (T_{min}), monthly total precipitation (Pre), monthly mean relative humidity (RH) and their annual mean variations at Songxian meteorological station from 1963–2018

Table 1 Statistics of tree-ring chronologies for LBL01 and LBL02

Chronology characteristics	Samples (core/tree)	Time span	Mean sensitivity (MS)	Standard deviation (SD)	Common period (period)	Mean inter-series correlation (R1)	Mean correlation within a tree (R2)	Mean correlation between trees (R3)	Subsample signal strength (SSS) > 0.85 (trees)	Signal-to-noise ratio (SNR)	Expressed population signal (EPS)
LBL01	40/22	1841–2021	0.22	0.19	1983–2012	0.24	0.55	0.24	1883(12)	12.87	0.93
LBL02	39/20	1787–2021	0.22	0.19	1983–2012	0.17	0.47	0.18	1863(16)	9.00	0.90

a sub-sample signal strength (SSS) threshold of 0.85 was taken as the standard to determine the starting year with 1883 and 1863, respectively. The mean sensitivity (MS) of all tree-ring chronologies in different slope directions was above 0.2, indicating that tree growth in the Lubanling is sensitive to environmental changes (Wu 1990). The smaller R1 and R3 values of the chronologies could be attributed to significant variations in the niches of the sampling sites. In subtropical areas, a warm and humid environment amplifies the differences among individual trees, and their growth is not entirely limited by the same factors (Li et al. 2021a). Higher signal-to-noise ratios (SNR), 12.867and 9.001, and expressed population signals (EPS), 0.928 and 0.9, demonstrate a high level of accuracy for these chronologies and higher environmental information.

Relationship between tree growth and climatic factors

Correlations between tree growth and climate factors

Correlation analyses between the two standard chronologies and climate factors showed that the chronologies of LBL01 and LBL02 sites had significant negative correlations with T_{max} and T_{mean} in the previous June–August and the current May–July, and significant positive correlations with Pre in the current May and RH in the current May–July (Fig. 4). The LBL01 chronology also showed significant negative correlations with T_{min} in the previous June–August and the current May–July. However, the LBL02 chronology also showed significant positive correlations with T_{mean} and T_{min} in the current February, the T_{max} in the current September, the Pre in the previous December and the current May–July, the RH in the previous June–August, December and the current March, August, and significant negative correlations with Pre in the previous April.

Therefore, temperatures in the previous June–August and the combination of temperatures and moisture in the current May–July were the main limiting factors for the growth of *P. armandii* in the Lubanling.

Variation in relationships between tree growth and climate factors

The moving correlation analysis results (Fig. 5) showed that the response of tree-ring width chronologies on different slopes to climate change during 1962–2019 were relatively stable, but some changes took place. With the change in climate, The response of the LBL01 chronology was stable with the T_{mean} in the current June–July, Pre and RH in the current May. The stability of the LBL01 chronology and the T_{mean} in the previous June–July and current May, RH in the current June changed to some extent. The response of the LBL02 chronology was stable with the T_{mean} in the current

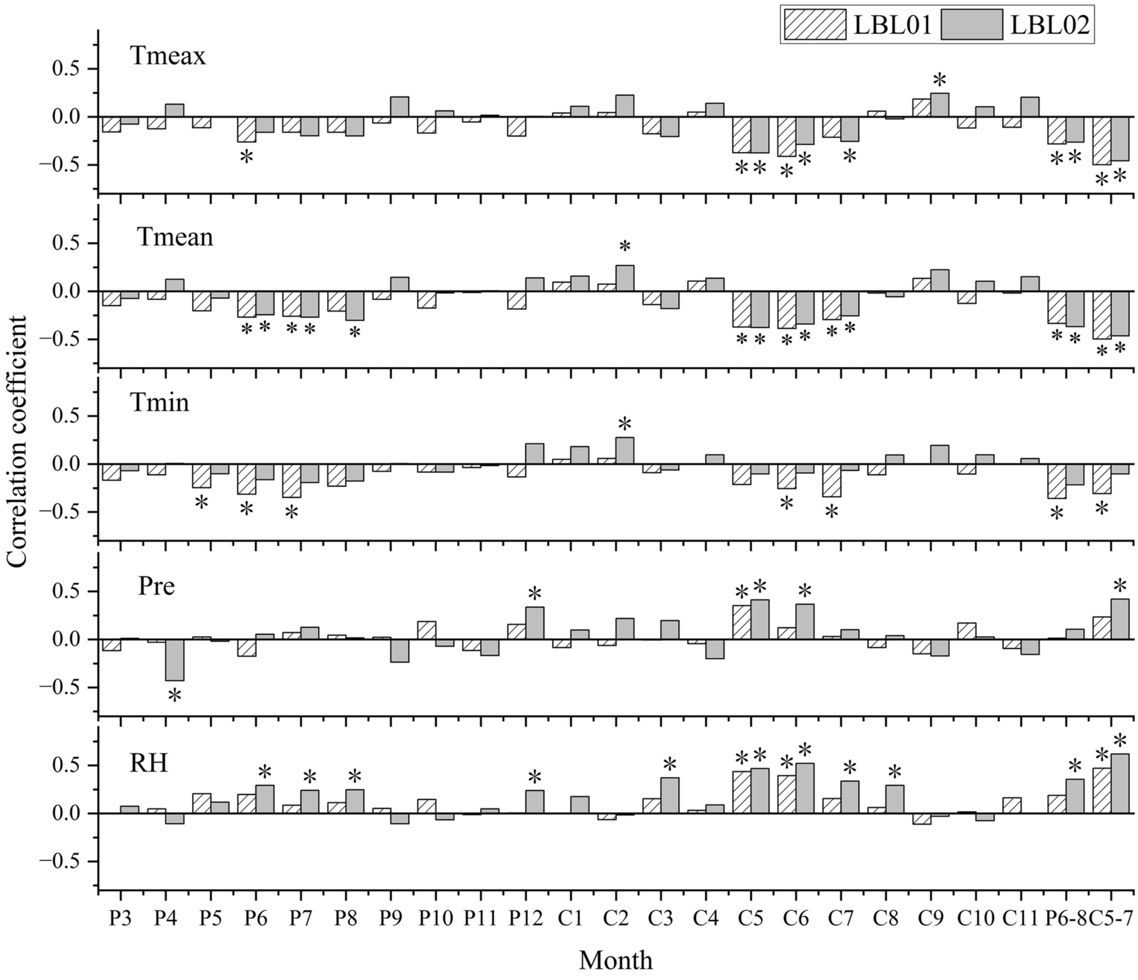


Fig. 4 Correlation coefficients between tree-ring chronologies at different points and T_{max}, T_{mean}, Tmin, Pre and RH. * indicates above 95% confidence level; P: Previous year, C: Current year

February, May and July, Pre in the previous December, RH in the previous August, December and current March, May and July. The stability of the LBL02 chronology and the T_{mean} in the previous June–August, and the current June, Pre in the previous April and current June, RH in the previous June- July, and the current June, August changed to some extent.

Discussion

The correlation coefficient of the two chronologies was 0.581 ($p < 0.01$), indicating that tree radial growth at the LBL01 and LBL02 sites were consistently affected by some common environmental factors (Cui et al. 2021). However, slope aspect can change heat and moisture regimes by regulating solar radiation, and different slope directions have different sunshine duration, snow cover time, growing season length and other factors affecting radial growth (Guo et al. 2016).

With the change in climate, the limiting effect of climatic factors on radial growth changed significantly. Previous studies (Briffa et al. 1998; Wilmking et al. 2004; D'Arrigo et al. 2008; Jiao et al. 2022) showed that "sensitivity change" was widespread in the Northern Hemisphere since the second half of the twentieth century and the formation mechanism is complex there is still uncertainty about the possible causes. Moreover, different slope directions also have an influence on the "sensitivity change" (Wilmking 2005; Gai et al. 2017). This study selected the diurnal temperature range (DTR) of the same month (Wilson and Luckman 2002, 2003) to explain the cause of the "sensitivity change". The change of DTR is mainly due to the change of cloud cover. On one hand, it reflects solar radiation on to the surface during the day, resulting in a decrease of the maximum temperature. At the same time, it absorbs surface long-wave radiation at night and releases the corresponding long-wave

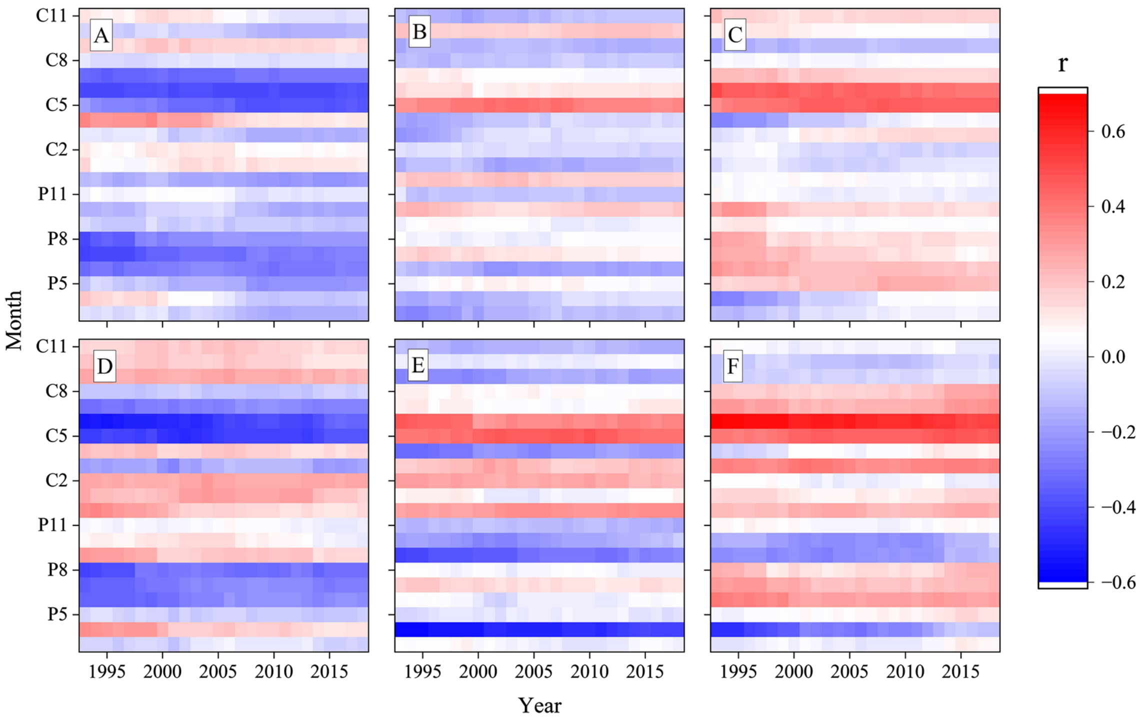


Fig. 5 Moving correlation results between two residual chronologies and T_{mean}, Pre, RH. A, B, C: the moving correlation results between LBL01 chronology and T_{mean}, Pre, RH, respectively; D, E, F: the moving correlation results between LBL02 chronology and T_{mean}, Pre, RH, respectively

radiation to heat the atmosphere, thus leading to an increase in minimum temperatures (Easterling et al. 1997; Buentgen et al. 2013). The moving correlation coefficients of LBL01 and LBL02 with the month in which the "sensitivity change" occurred showed the same or opposite trend to the 30-year moving mean of DTR in the same month (Fig. 6) and a good correlation (Fig. 7), indicating that the cause of the "sensitivity change" may be related to the variation of DTR in the same month to some extent.

Common analyses of climate-growth relationships on different slope directions

Correlation analysis showed that the chronologies of different slope directions were mainly affected by the temperature of the previous June–August and the combination of temperatures and moisture in the current May–July. Temperature in the previous June–August had a negative effect on radial growth. This may be due to higher temperatures leading to a decrease in photosynthesis, partial closure of leaf stomata, and reduction of organic matter synthesized by photosynthesis, which were not conducive to radial growth and might slow growth the following year (Liu et al. 2014; Hui et al. 2017; Cui et al. 2021; Guo et al. 2022a), consistent with the results of Li et al. (2020) for *P. armandii* in Muzhaling. However, with the change in climate, the negative responses of radial growth and the temperature in the previous June–August gradually decreased, consistent with the results of Yang et al. (2021b) for *Larix gmelinii* Rupr. in the Greater Hinggan Mountains and those of Cao et al. (2020) for *Abies georgei* Orr and *Tsuga dumosa* (D. Don) Eichler in Laojun Mountains, Lijiang. This may be due to an increase in cloud cover caused by lower DTR, reducing drought stress caused by intense solar radiation (Li et al. 2010).

The rainy season had not yet arrived in May–July (Fig. 3), and high temperatures enhanced soil evaporation and plant transpiration, resulting in rapid water dissipation in trees and insufficient water supply for photosynthesis, thus indirectly restricting radial growth and forming relatively narrow rings (Yu et al. 2005a; Li et al. 2021b; Yang et al. 2021a). The increase in humidity can alleviate the transpiration of soil water caused by rising temperatures, which is conducive to the storage of more water to meet growth demand. The increase in precipitation during this period is favorable in alleviating water shortage (Wang et al. 2010). Relative humidity has a stronger limiting effect than precipitation on *P. armandii* due to the altitude (1900 m) in Lubanling, the frequency of fog, and the high relative humidity. Dense clouds often form which reduce the intensity of solar radiation and temperatures, thus alleviating the problem of water shortage (Yu et al. 2005b; Li et al. 2021c). This is consistent with research results in

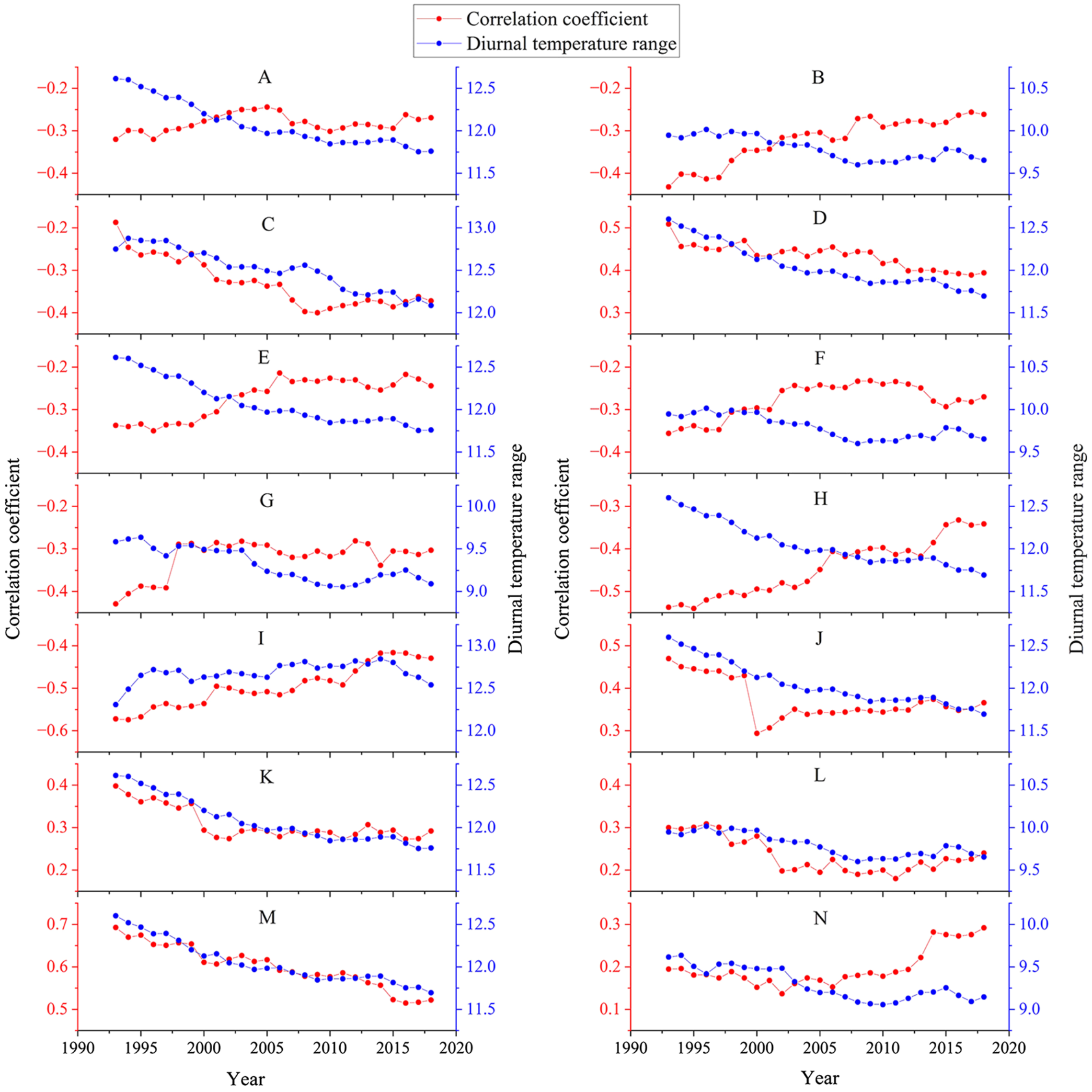


Fig. 6 Trend of moving correlation coefficients and 30-year moving average values of DTR in the month when "sensitivity change" occurs A–D: the moving correlation coefficients between LBL01 and T_{mean} in previous June, July, current May, RH in current June and the 30-year moving average of DTR of the same month, respectively; E–N: the moving correlation coefficients between LBL02 and T_{mean} in previous June, July, August, current June, Pre in previous April, current June, RH in previous June, July, current June, August and the 30-year moving average of the DTR of the same month, respectively

the Funiu Mountains (Tian et al. 2009; Wang et al. 2016; Cui et al. 2021; Li et al. 2022) and surrounding areas (Peng et al. 2014; Peng and Wang 2015; Cai et al. 2019). With the change in climate, the response to temperature in the current July, precipitation and relative humidity in the current May were relatively stable, and the positive response to relative humidity in the current June gradually decreased. This may be due to an increase in cloud cover caused by lower DTR, which led to an increase in precipitation, easing the drought stress that month (Zhang et al. 2017). There are some differences in the response to different slopes to temperature in the current May–June.

Analyses of different climate-growth relationships on different slopes

Although the chronologies of different slope directions were mainly affected by temperatures in the previous June–August and the combination of temperatures and moisture in the current May–July. The chronology on the northern slope was affected by the combined maximum and minimum temperatures. Higher moisture and night temperatures promoted enhanced respiration which restricted growth (Guo et al. 2016; Cui et al. 2021). The chronology on the western slope was influenced by maximum temperatures, consistent

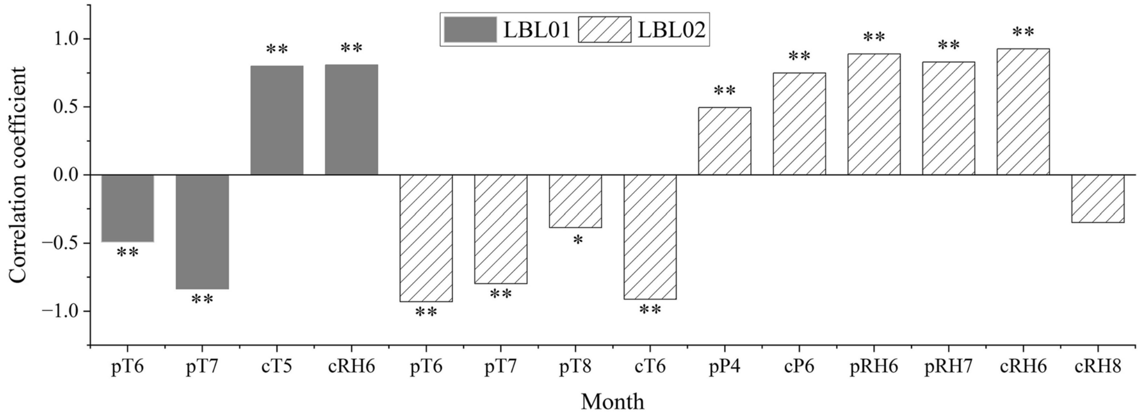


Fig. 7 The moving correlation coefficients of the month with the "sensitivity change" and the 30-year moving average of DTR in the month

with Guo et al. (2016) and Cui et al. (2021). With the change in climate, the negative response of the LBL01 site on the northern slope to temperature in the current May gradually increased, the temperature on the northern slope was relatively low, and with its increase, DTR decreased. Nighttime temperatures increased significantly and respiration was magnified, which further enhanced the limit of temperature on tree growth in the current month (Barber et al. 2000; Cui et al. 2021; Li et al. 2021b). However, the temperature response of trees on the LBL02 site on the western slope was stable with that in the current May.

The temperature response of LBL01 trees on the northern slope was stable in the current June. But the negative response of LBL02 trees on the western slope to the temperature in the current June gradually decreased. This is similar to studies of *Pinus taiwanensis* Hayata and *Pinus massoniana* Lamb in the Dabie Mountains (Cai et al. 2019), *L. gmelinii* (Rupr.) Kuzen in the Greater Khingan Mountains (Sun et al. 2019), *Abies fargesii* Franch in the Himalayas (Yadav et al. 2004), and studies of species in the high latitudes in the Northern Hemisphere (Jacoby and D'Arrigo 1995; Briffa et al. 1998). The temperature on the western slope was relatively high, and with its increase, DTR decreased, alleviating the drought stress caused by the strong solar radiation in the month. (Li et al. 2010).

On the northern slope, temperatures were low and humidity high, and the limits of water on radial growth was not a constraint. On the western slope, temperatures were high and humidity low, and water constraints on radial growth was significant (Cui et al. 2021). Tree radial growth on the LBL02 site on the western slope was also affected by precipitation in the previous April, December and in the current June, and the relative humidity in the previous June- August, December and in the current March and July–August. The excessive precipitation in previous April caused a decrease in temperature, delaying the start of the growing season and reducing the accumulation of nutrients (Li et al. 2011). With the change in climate, the negative response to precipitation in the previous April gradually decreased; this is consistent with the results of Guo et al. (2022a). The increase in DTR may increase on sunny days, slowing down the effects of precipitation- induced cold temperatures on tree growth (Lloyd and Fastie 2002; Zhang et al. 2011; Guo et al. 2022b; Liu et al. 2022). Precipitation and relative humidity in the previous December was mainly in the form of snow, which reduced soil heat emissions and blocked the entry of cold air to the soil. However, snow can also increase soil moisture content and compensates for the scarcity of water during tree growth and provide sufficient moisture for growth and germination in the following year (Guo et al. 2022b). With an increase in temperature and a decrease in humidity, the response of radial growth to precipitation in the previous December and relative humidity in the previous August, December and in the current March and July was relatively stable. The positive response of radial growth to precipitation in the current June and to relative humidity in the previous June–July gradually decreased, consistent with the results of Jiao et al. (2019), Liu et al. (2022) and Guo et al. (2022b). The temperature on the western slope was relatively high, and with its increase, DTR decreased, alleviating the drought stress caused by the strong solar radiation in the month (Li et al. 2010). The positive response of radial growth and relative humidity in the current August changed somewhat but the correlation coefficients were different from the change of DTR. The reasons for the change may be related to other factors (complex non-linear or threshold responses, local pollution, and detrending end effect) (D'Arrigo et al. 2008).

In summary, the radial growth of *P. armandii* in this region was mainly influenced by temperatures from the previous June to August and the combination of temperatures and moisture in the current May to July, while there was some significant difference due to the sampling sites on different slopes. Tree growth on the western slope was more sensitive to climate, but the difference in response from trees on the two slopes gradually decreased with the increase in temperatures. This was in contrast to the results of *Picea purpurea* Mast. and *Abies faxoniana* Rehd. & E,H, Wilson on the western Sichuan (Guo et al. 2016) and may be due to the difference in species..

Conclusions

In this study, tree ring-width chronologies of *P. armandii* were established for trees on different slope directions. Higher mean sensitivity (MS), signal-to-noise ratio (SNR) and expressed population signa (EPS) demonstrated high environmental information in the chronologies.

Correlation analyses indicated that temperatures in the previous June–August and combination of temperatures and moisture in the current May–July were the main limiting factors to radial growth of *P. armandii* in the Lubanling. The different response of trees on the two slopes to climate was small but not neglectable. Tree radial growth on the northern slope was mainly affected by the combined maximum and minimum temperatures, while tree radial growth on the western slope was mainly affected by maximum temperatures. Radial growth on the northern slope was mainly affected by the relative humidity in the current May–July period, while on the western slope, it was mainly affected by the relative humidity of the previous June–August, of the current May–July and precipitation in the current May–July.

With the change in climate, the stability of climate response of *P. armandii* showed minor changes, which may be due to changes in the diurnal temperature range due to the different slope directions. Further, differences between tree radial growth and climate response on the northern and western slopes gradually decreased. From a perspective of climate influence on tree radial growth, this study indicates a possible influence of future temperature rise on the radial growth of *P. armandii* with on different slopes which is of considerable significance.

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