EXPLORING THE DIFFERENTIATION EFFECT BETWEEN *LARIX KONGBOENSIS* AND TEMPERATURE AND PRECIPITATION IN THE SOUTHEASTERN TIBETAN PLATEAU OF CHINA

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Abstract. *Larix kongboensis* is a tree species indigenous to Tibet and sometimes mistaken for *L. griffithii*. At present, the population of *L. kongboensis* is dwindling as a result of urban growth. This experiment intends to determine the responsive connection between *L. kongboensis* standard chronology and climate change using analysis methods in tree-ring climatology and combining them with climate change features of the study region. This correlation study was undertaken to determine whether a “differentiation impact” on the radial development of *L. kongboensis* exists before and after the climatic change. We also aim to verify if a clear difference is observed between the radial orientation of *L. kongboensis* and weather conditions at two different heights. Combined with the tree-ring climatology method, Mann–Kendall test was used to assess the timing of abrupt temperature changes in the study region by cross-referencing the *L. kongboensis* standard chronology (STD). We also utilized sudden temperature change as the dividing line to explore the response connection between *L. kongboensis* and limiting influencing elements in the research region by comparing the degree of response of climatic factors to the radial growth of *L. kongboensis* before and after the abrupt change. We examined how the radial growth of *L. kongboensis* changed as a result of climate variables after rapid climate changes using moving correlation. We then compared the differences between different altitudes. The findings of the correlation analysis are presented as follows: (1) The radial growth of *L. kongboensis* was severely constrained by the maximum temperature in the early part of the growing season and the correlation between the radial growth from February to June of the same year and the maximum temperature changed from a positive correlation ($P > 0.05$) to a significant negative correlation ($P < 0.05$) after the abrupt shift in temperature. The minimum temperature changed from a mostly negative correlation to a mostly positive correlation. Precipitation and relative humidity were significantly more suppressed than those before the abrupt temperature change. (2) Moving correlation demonstrated that the negative reaction of the maximum temperature to the radial development of trees of both species increases in *L. kongboensis* in both research sites during the growing season, particularly in the early stages of the present growing season. (3) Lower-elevation radial development was hampered more than higher-elevation radial development, with precipitation exerting a significantly greater impact at higher elevations. Results indicated that the response of radial development to climatic conditions for the same tree species in two distinct environments differs significantly. The influence on the radial development of trees is neither completely prevented nor accelerated and “divergence problems” are observed in various months when a sudden temperature change occurs.
Keywords: *tree ring, climate response, altitudinal gradient, divergence problem, Larix kongboensis*

Introduction

Forests are a crucial component of the ecosystem cycle that has attracted considerable academic interest throughout the years. The correlation between the radial development of trees and temperature increases while the correlation with precipitation reduces as the elevation rises according to the classic understanding of the tree growth process (Zhang et al., 2017; Meng et al., 2021; Pandey et al., 2020; Truettner et al., 2018). The ideal environment for tree growth has steadily diminished due to the temperature rise caused by global warming. For instance, Natalini et al. (2015) noticed a considerable reduction in radial growth of Italian stone pine (*Pinus pinea*) in southern Spain and Portugal as a consequence of rising temperatures. Tei et al. (2014) discovered that rising precipitation inhibits the radial development of *L. cajanderi* in East Siberia. Rahman et al. (2018) discovered comparable results in the tropical rainforest of Rema-Kalenga Wildlife Sanctuary. However, studies conducted in some regions have shown that temperature changes exert a major impact on the development of plants on the plateau (Tso et al., 2022; Xu et al., 2017). The influence of temperature on trees may stimulate their radial development. The occurrence of substantial disparities in tree development is known as the “divergence problem” (Nie et al., 2021; Luo et al., 2022). Exploring the response link between the radial growth of trees and climate change in different locations is crucial in projecting forest development and the protection of the ecological environment in the 21st century.

Significant temperature changes at high elevations of the Qinghai–Tibet Plateau, which is a vulnerable area exposed to global climate change, have been reported since the 1990s (Xue et al., 2021; Soulé et al., 2021; Rodriguez–Caton et al., 2021; Jevšenak et al., 2021). Researchers have become increasingly concerned about the development of trees and their temperature sensitivity as temperatures continue to rise (Marques et al., 2018; Comeau et al., 2019). Although the “divergence problem” has been extensively investigated, new insights into the relationship between altitude and time scale for high-altitude regions are still necessary. At present, the radial development of trees at high altitudes combined with the interaction among trees, temperature, and precipitation pursuing considerable changes is significantly affected by global climatic variation. Can we learn more about the effect of global temperatures on high altitudes by analyzing these changes? Are trees at high altitudes susceptible to temperature extremes (both maximum and minimum)? Are responses of the same tree species to inclement climate the same at different elevations? On this basis, the relationship between radial growth and climatic parameters in *L. kongboensis*, which is an indigenous tree species in Shergyla Mountain in Tibet, is examined in this work under various growing circumstances. Moreover, the relationship between radial growth and temperature change is analyzed by combining the “divergence problem”. We hypothesize that differential impacts occur between radial growth and temperature and precipitation in *L. kongboensis* growing at various elevations, precipitation and relative humidity responses of trees at high altitudes will differ significantly, and the difference between the minimum temperature and precipitation at different elevations will be significant.

Materials and methods

Overview of the study area

Shergyla Mountain is situated in the southeast of Tibet and is a part of the Nyingchi Tanggula mountain range, which runs from southwest to northeast of the whole Tibetan territory. Hence, the warm current from the Indian Ocean and the cold current from the northwest are isolated to safeguard the ecological security of the southeast area of Tibet and divide the Tibetan area into southern and northern parts physically. The Shergyla Mountain region is rich in vegetation with high species variety and a large altitude

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gradient (400–7500 m), and the forest vegetation changes remarkably along the height gradient from alpine broadleaf forest to alpine meadows (Gao et al., 2020; Jing et al., 2005; Shao et al., 2019). Based on Local Meteorological Positioning Station and NOAA Annual Data (https://www.noaa.gov) the average temperature of the area is 8.3 °C, which is consistent throughout the year. The minimum temperature of the year often happens in January (mean monthly temperature of 0.2 °C), whereas the maximum temperature of the year usually occurs in July (mean monthly temperature of 15.6 °C) (*Fig. 1*). Relative humidity reaches 67.8%. Annual mean precipitation (MAP) is 762.8 mm, with the majority of precipitation occurring between June and September (>120 mm each month) (*Fig. 1*). According to field-measured meteorological data from the last 50 years and the *Blue Book on Climate Change in China 2020* published by the Climate Change Center of the China Meteorological Administration in 2020, a more pronounced rise in temperature and precipitation in high-altitude regions has been observed and the frequency of severe weather has increased substantially.

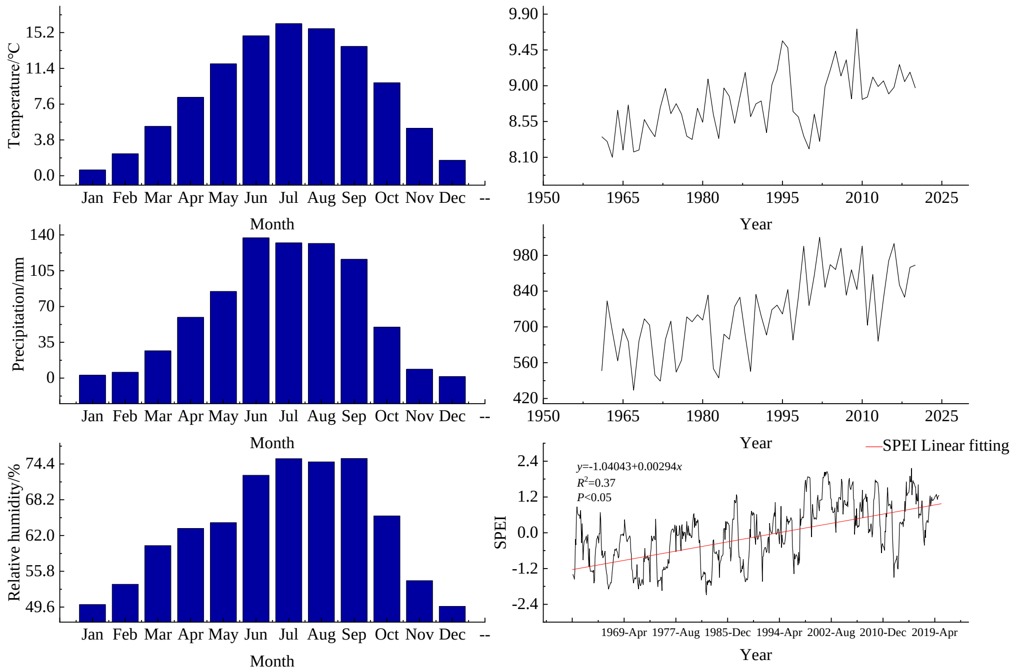

Figure 1. *Characteristics of climate factors in the study area*

Experimental area

This study focuses on Lulang Town (LL) and Jialuo (JL), which are situated in the eastern portion of Nyingchi City. The growth range of the endemic tree species *L. kongboensis* is severely restricted in this region due to the effect of the geographical environment and genetic traits of trees. The two research regions correspond to the lowest and highest points (3000 m, 3600 m) of the optimal altitude range for *L. kongboensis*. The growing age of *L. kongboensis* is short under the effect of human activities. The ecological structure of *L. kongboensis* is stable, with a wide variety of understory vegetation, in the research region (*Table 1*).

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Table 1. *Basic characteristics of plots*

Site	Longitude	Latitude	Elevation	Slope	Slope aspect	Crown density	Forest vegetation
LL-3100-1	94°44′24.78″	29°49′11.27″	3100	13°	S	35%	*Pseudognaphalium affine*, *Epipactis helleborine*, *Anaphalis aureopunctata* var. *atrata*, *Sambucus adnata*, *Lonicera nigra*, *Salix daltoniana*, *Rhododendron triflorum*, *Rubus fockeanus*, *Elsholtzia fruticosa*, *Rodgersia podophylla*, *Iris bulleyana*, *Rosa omeiensi*, *Anemone rivularis*, *Sinopodophyllum hexandrum*, *Thalictrum aquilegiifolium* var. *sibiricum*, *Impatiens linghziensis*
LL-3100-2	94°44′24.80″	29°49′11.28″					
LL-3100-3	94°44′24.83″	94°49′11.29″					
JL-3600-1	94°33′12.69″	29°33′44.42″	3600	33°	N	60%	*Anaphalis aureopunctata* var. *atrata*, *Polygonum macrophyllum*, *Rhododendron triflorum*, *Smilax menispermoidea*, *Cynoglossum furcatum*, *Fragaria nubicola*, *Rosa omeiensis*, *Fragaria moupinensis*, *Anemone rivularis*, *Geranium wilfordii*, *Viola biflora*, *Lonicera nigra*, *Primula florindae*, *Galium spurium*, *Impatiens linghziensis*, *Polygonatum verticillatum*, *Senecio analogus*, *Athyrium sinense*
JL-3600-2	94°33′12.71″	29°33′44.43″					
JL-3600-3	94°33′12.75″	29°33′44.44″					

Sample gathering and chronology production

Tree-ring samples were obtained at elevations of 3100 and 3600 m in July 2021 (*Table 1*). Upright trees with entire trunks, without insect infestation, and distantly located from the roadway were selected for sample collection. Tree cores were drilled in both the north-south and east-west directions along the diameter at breast height (h = 1.5 m) using an increment borer (D = 5.15 mm), and a total of 120 sample cores were obtained in the research region. Samples were first collected for visual inspection and determination of initial integrity and then placed in shock-absorbing containers. Cores are placed in a precise wooden groove in a cool area to dry naturally and then sanded in stages with 100-, 200-, 400-, and 600-grit sandpaper until the distinction between early and late wood is visible to the naked eye. The gathered core widths were placed on a Lintab^{TM} 6.0 tree wheel width meter for measurement (accuracy of 0.01 mm). Pseudoannuli in core samples were originally deleted based on eye examination, in which 10% of the samples were excluded and considered inferior and two samples from the same tree species were cross-referenced. The measurements were entered into a TASP-Win computer for secondary cross-dating examination, during which missing chronologies were restored and chronological loops were reviewed. *L. kongboensis* tree cores were standardized with the negative exponential function and double weight (Fritts, 1971; Douglass, 1933) using the ARSTAN program, and the completed tree cores were subjected to secondary confirmation before the comparison of the two validation results.

Figure 4 shows the comparison of characteristic curves of the change in the annual ring width index of *L. kongboensis* at the two sample locations of LL and JL. The 63-year chronology (1953–2020) of *L. kongboensis* in the LL region was depicted. *L. kongboensis* presents a reliable chronology of 47 years (1973–2020) in the JL area. The chronology of *L. kongboensis* in the LL area indicated a rising tendency from 1957 to 1984 and a falling trend from 1985 to 2020 due to the abrupt temperature change. *Figure 3* illustrates the consistent trend of temperature.

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Climate data

Meteorological data were selected from the Nyingchi National Forest Ecosystem Observation & Research Station of Tibet (29°38′41.87″ N, 94°42′36.90″ E, altitude: 3800 m) (*Fig. 2*), which is located very near the study site. National Oceanic and Atmospheric Administration (NOAA, https://www.ncei.noaa.gov) and China Meteorological Data Service Centre (http://data.cma.cn) (Lun, 2018) are complementary. Average precipitation (P), relative humidity (RH), average temperature (T_{mean}), maximum temperature (T_{max}), and minimum temperature (T_{min}) are selected from data from weather stations from 1961–2020. SPEI is the correlation analysis among six indicators, and the chronology of tree-ring SPEI is computed using R, where the calculation method is referenced to Thornthwaite and the associated procedure is referenced to (http://www.csdata.org/p/217). A part of the formula for SPEI is expressed as follows (*Eqs. 1-7*):

$$PET = \begin{cases} 0 & T < 0 \\ 16(N/12)(NDM/30)(10T/I)^m & 0 \leq T < 26.5, \\ -415.85 + 32.24T - 0.43T^2 & T \geq 26.5 \end{cases} \quad \text{(Eq.1)}$$

$$I = \sum_{i=1}^{12} (T/5)^{1.514}, T > 0, \quad \text{(Eq.2)}$$

where T represents the monthly average temperature, N represents the maximum daylight hours, NDM represents the number of days per month, and I represents the yearly heat index.

$$D_i = P_i - PET_i, \quad \text{(Eq.3)}$$

$$D_n^k = \sum_{i=0}^{k-1} (P_{n-i} - PET_{n-i}), n \geq k, \quad \text{(Eq.4)}$$

$$f(x) = \beta/\alpha \, (x - \gamma/\alpha)^{\beta-1} [1 + (x - \gamma/\alpha)^{\beta}]^{-2}, \quad \text{(Eq.5)}$$

where α is the scale coefficient, β is the shape coefficient, and γ is the origin parameter.

$$F(x) = \left[1 + (\alpha/x - \gamma)^{\beta}\right]^{-1}, \quad \text{(Eq.6)}$$

$$SPEI = W - C_0 + C_1W + C_2W^2 / 1 + d_1w + d_2w^2 + d_3w^3, \quad \text{(Eq.7)}$$

where W is a parameter with a value of $\sqrt{-2 \ln P}$ and $C_0 = C_1 = C_2 = d_1 = d_2 = d_3 = 2.515517$ are other constants in the equation.

The Pearson correlation analysis technique was used to examine the association between temperature and precipitation in the Shergyla Mountain region and the LL-3100 and JL-3600 tree chronologies from 1961 to 2020. Bootstrap1000 sampling test was employed to determine the sample size. $P < 0.05$ was the criterion used to generate the data. Manner–Kendall mutation test was computed using R to estimate the time of the rapid shift in temperature in the research region with the necessary protocol (https://blog.csdn.net/article/details/102524239) as follows (*Eqs. 8-10*):

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$$S = \sum_{i=1}^{k} r_i \quad r_i = \begin{cases} 1, x_i > x_j \\ 0, \ else \end{cases} j = 1,2, \ldots, i, \quad \text{(Eq.8)}$$

$$UF_k = \frac{S_k - E(s_k)}{\sqrt{Var(s_k)}} \quad k = 1,2, \ldots, n, \quad \text{(Eq.9)}$$

where $E(s_k) = n(n-1)/4$ and

$$Var(s_k) = n(n-1)(2n+5)/72 \quad \text{(Eq.10)}$$

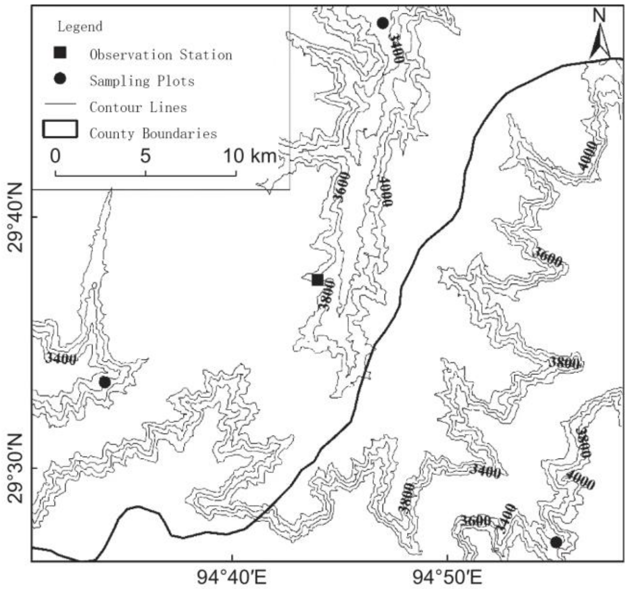

Figure 2. *Mapping of sample plots and observation stations in the study area*

Results

Mann–Kendall temperature test mutation

The Mann–Kendall (M–K) nonparametric test (*Fig. 3*) was used to explore the abrupt change points and years of meteorological data. Meanwhile, UF and UB of the mean temperature were computed, and the intersection of UF and UB was utilized to estimate the abrupt change time of the temperature. Note that abrupt change points were within the interval ± 0.05. The significant change in average temperature in the study region was concluded to have occurred in 1984 and the abrupt change in precipitation occurred in 1992 after the standard chronology of *L. kongboensis* was adopted for the tree-ring chronology (*Fig. 4*) and the results were cross-referenced with those of the Mann–Kendall test. The abrupt change time in the study area is divided into two timeframes based on the sudden change time of the average temperature. Meanwhile, the abrupt change time of the texture and precipitation is also divided into two time periods. The two time periods before and after the abrupt change in mean temperature (1961–1984) were compared (1985–2020).

The findings of the two experiments were exported upon confirmation of their consistency, and a chronology of tree wheel widths was constructed using COFECHA (*Table 2*).

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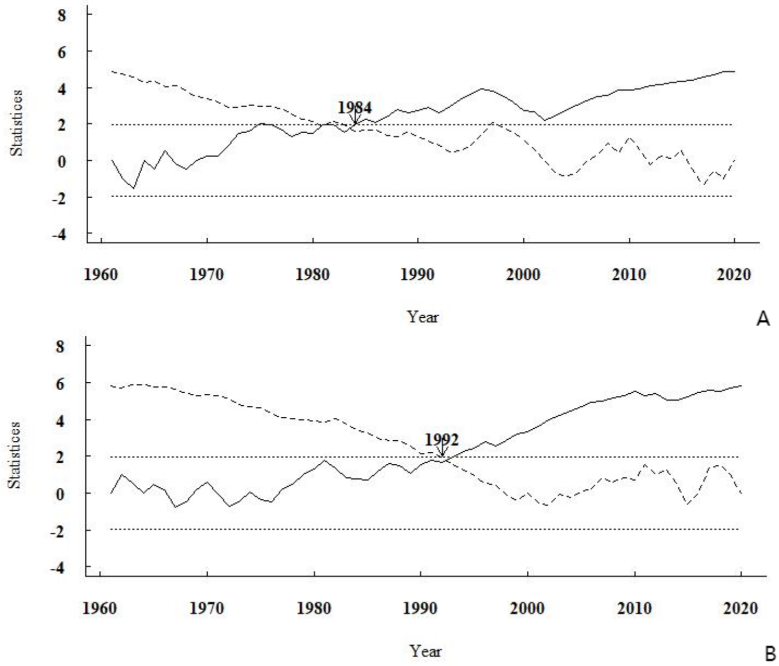

Figure 3. *Mann–Kendall method of temperature (A) and precipitation (B)*

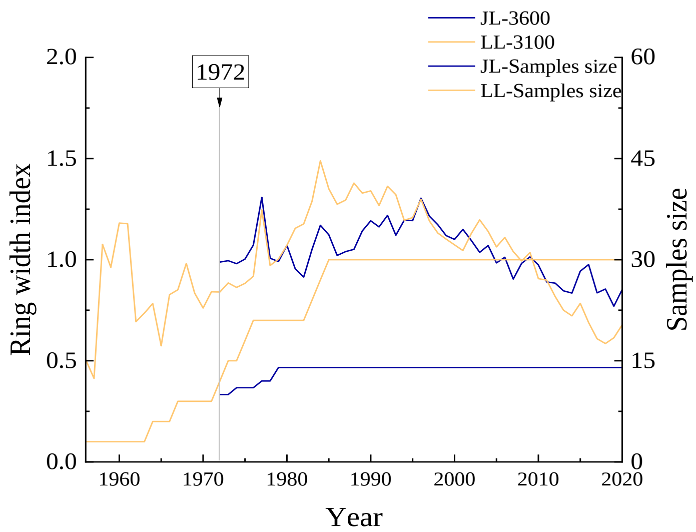

Figure 4. *Ring width index of Lu Lang and Jia Luo of L. kongboensis. JL-3600: At an altitude of 3600 in Jialuo; LL-3100: At an altitude of 3100 in Lulang*

Tree-ring information

Characterization statistical of tree chronology at sampling places (*Table 2*), Maximum age of tree rings (SSS), Mean sensitivity (MS), Standard deviation (SD), and Mean-intra-tree correlation (R1) is greater, illustrates that tree chronology is more responsive to weather variables. Highly signal-to-noise ratio (SNR) illustrated that climatic factors included in the chronology are significant. Moreover, the quality of the chronology and the extent of weather data are excellent, and first-order autocorrelation

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(AC1) is over 0.2. This finding indicated that climate elements of the previous year exert a significant impact on the radial growth of trees, thereby facilitating the understanding of the "lag effect" of temperature changes. The first principal component (PC1) and expressed population signal (EPS > 0.85) indicated that the gathered tree core samples are representative of the entire research area and information in the chronology is sufficient for the next step of response analysis.

Table 2. *Main statistical characteristics of the two tree-ring width chronologies*

Tree Cores	Samples	SSS	R1	MS	SD	EPS	SNR	AC1
LL	30/30	1957	0.319	0.122	0.168	0.911	19.538	0.361
JL	24/30	1973	0.8	0.22	0.25	0.98	9.52	0.24

Response of radial growth to temperature and precipitation

We evaluated whether significant differences exist in the radial growth of *L. kongboensis* across areas to determine the connection between the radial development of *L. kongboensis* and the external environment in response to global warming. The growing season of *L. kongboensis* in Shergyla Mountain was estimated to be between May and October according to the tree growth activity in the study area and the physiological activity of native trees. The study also revealed that a significant "lag effect" exists between tree growth and climate changes that began during the mid-growth period in July. The correlation between temperature and precipitation from July of the prior year (P7) to October of the current year (C10) and the standard chronology of *L. kongboensis* were adopted in this study. As illustrated in *Figure 5,* significant differences were observed between the JL and LL chronologies and the temperature and precipitation from 1961–2020. The mean temperature from July to August exerted a significant limiting effect on the radial growth of JL with a significant lag. The maximum temperature stimulated the radial growth of JL whereas the minimum temperature limited its growth in the early growing period (January–April of the current year). The radial growth of JL was significantly prevented by precipitation in February and after the growing period (October), while the relative humidity affected the radial growth of JL throughout the growth period (May and July). Mean temperature, maximum temperature, precipitation, and relative humidity revealed significant lag effects on the radial growth of JL. Comparatively, the minimum temperature from February–April presented a more significant effect on the radial growth of LL. A negative correlation was observed between the beginning growing season (February and March) precipitation and growth season relative humidity (May–September). This finding illustrated that minimum temperature, precipitation, and humidity limit LL's radial growth. Compared with JL, "lag effects" of temperature minimally affect the radial growth of LL.

Although *L. kongboensis* in both LL and JL present similar genes and physiology, our study indicated that substantial differences exist across environments (Guo et al., 2022). *L. kongboensis* responds differently to the surrounding environment under the effect of the same exterior environmental factors. This different response was significant for the maximum temperature and precipitation of the initial growth season (C3-4).

Divergence problem of radial growth

Temperature changes in 1961–1984 and 1985–2020 were analyzed using tree standard chronology and MK test analysis, and the response of radial growth of *L.*

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kongboensis to temperature and precipitation in various research areas before and after the change was compared (*Fig. 6*). The mean temperature throughout the growing season presented a significant effect on JL's radial growth. The mean temperature in July, August, and November showed a significant "lag effect" and a significant correlation with the mean temperature in November of the previous year and January of the current year. The maximum temperature exhibited a more significant negative correlation with the tree radial growth in the early part of the growing season that changed from a significant positive correlation ($P > 0.05$) to a significant negative correlation ($P < 0.05$) from February to June of that year after an abrupt temperature change. The minimum temperature changed from mostly negative to a mostly positive correlation. Precipitation and relative humidity changed significantly compared with those before the temperature abrupt change, thereby indicating a significant negative correlation. The radial growth of LL is significantly affected by the relative humidity compared with that of JL. In addition to the negative correlations with May–July, and September of the current year, the precipitation in July and September exhibited a significant "lag effect" and a significant negative correlation.

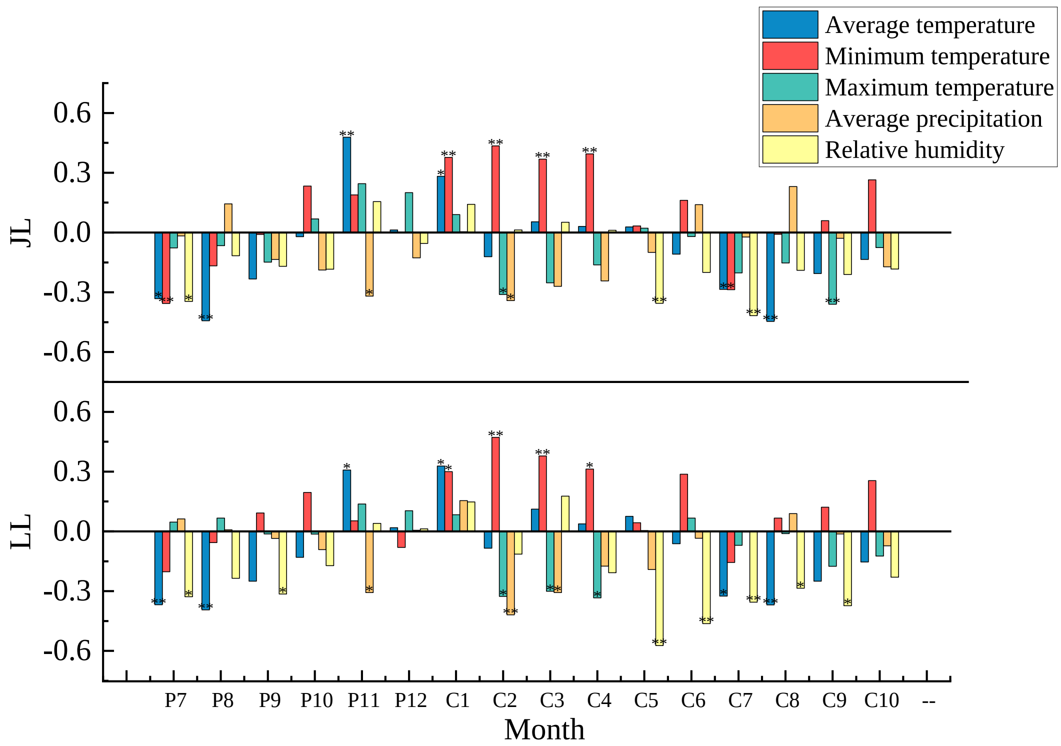

Figure 5. *Correlation coefficients between regional chronologies with climate factors in 1961–2020. Note: */** indicates the significance at a level of 0.05/0.01. JL: Jialuo; LL: Lulang; P indicates the months of the previous year, and C represents the month of this year*

The radial growth of LL was compared before and after the mutation, and the mean temperature in August of the year changed from a positive correlation to a negative correlation. Meanwhile, the "lag effect" was significantly enhanced. The maximum temperature changed from a positive correlation ($P > 0.05$) to a negative correlation for the radial growth of trees in the growing season (February and March). The minimum

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temperature exhibited a significant shift from being uncorrelated to a significantly positive correlation with the radial growth of LL. A significant positive correlation was observed between tree growth and temperature after a significant shift in mean temperature. Compared with the minimum temperature, precipitation showed a significant negative correlation with the growth of trees in the most abrupt temperature shift radial growth, and this inhibition was observed more significantly in the growing season. The relative humidity for the radial growth of LL changed from a negative correlation in the growing season to a negative correlation in the growing season (May–July, and September).

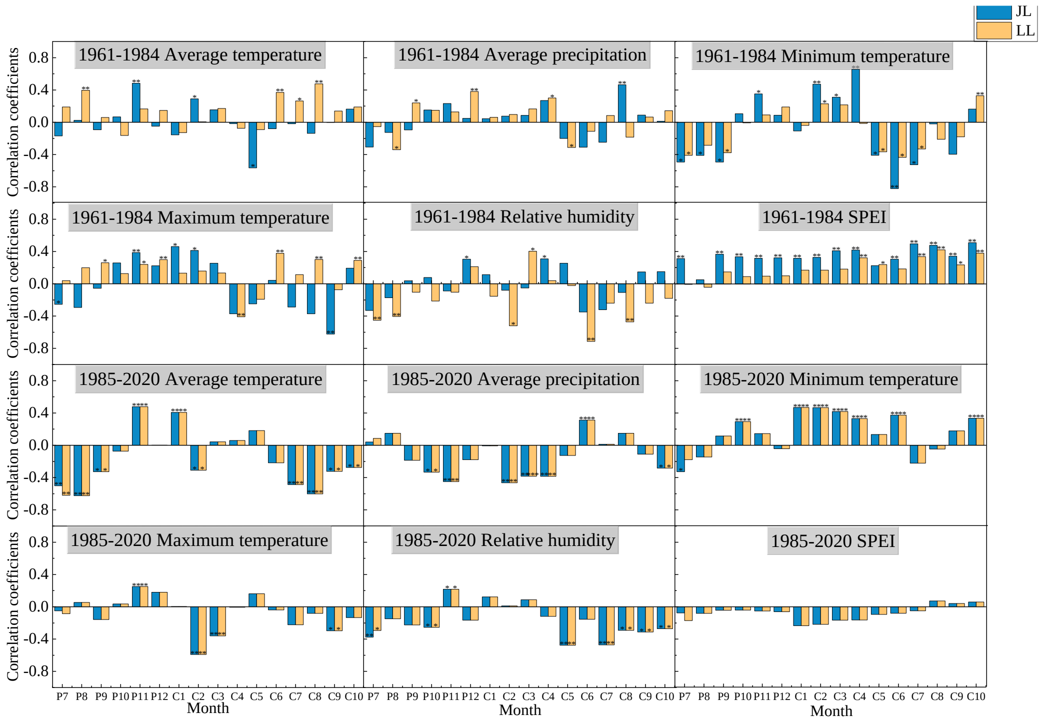

Figure 6. *Correlation between standard chronology and climatic factors before and after mutation. Note: */** indicates the significance at a level of 0.05/0.01. JL: Jialuo; LL: Lulang; P indicates the months of the previous year, and C represents the month of this year*

Moving correlation analysis of tree chronology and climate factors

As demonstrated in the previous paragraph, the growth of *L. kongboensis* is highly influenced by external climatic factors because the growth of *L. kongboensis* is intuitively affected by external climatic factors. Consequently, a moving correlation analysis was conducted to examine the pattern of radial growth of *L. kongboensis* in connection with climatic factors during the period of abrupt temperature change. Based on previous studies, a 30-year sliding window with a 5-year sliding step was adopted.

Sliding correlation analysis (*Fig. 7*) between *L. kongboensis* chronology and SPEI indicated that *L. kongboensis* and SPEI exert significant differential shifts between 1982 and 1987. The correlation between *L. kongboensis* radial growth and SPEI shifted to a negative correlation from 1977 to 2017 although the strong correlation weakened. The sliding correlation of the mean temperature from 1982 to 2017 demonstrated that the correlation between the mean temperature in July–September and the standard

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chronology of trees shifts from a positive correlation to a negative correlation; meanwhile, the "lag effect" increases significantly. The standard chronology of trees changed to a significant negative correlation with the mean precipitation in October from 1982 to 2017. The expression of the minimum temperature before and after the temperature change is unclear, but a change from a negative correlation to a positive correlation can be identified in the minimum temperature in some months, such as June and September. The significant correlation between the maximum temperature and the radial growth of trees reached a peak before and after the mutation, with a significant positive correlation with the radial growth in May-August and a significant "lag effect" with the maximum temperature in July and August.

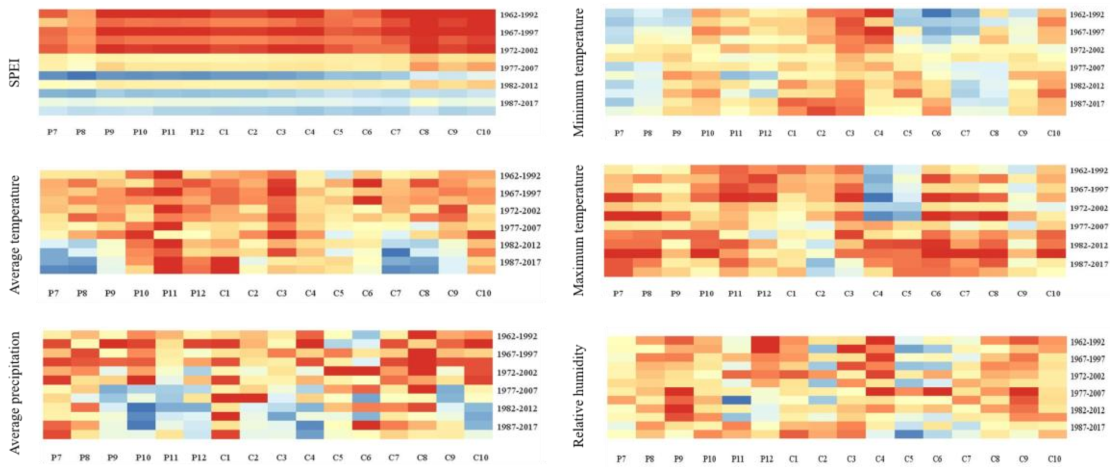

***Figure 7.** Moving correlation analysis between the tree-ring width chronology and climatic factors. Note: P indicates the months of the previous year and C represents the month of this year*

Effect of elevation on radial tree growth

As shown in the previous section, the abrupt change time of temperature and precipitation in the outside environment was identified using the standard chronology of *L. kongboensis* with temperature and precipitation for the mutation test. The M–K test analysis demonstrated that *L. kongboensis* presents a significant response correlation with the climate change response of the environment at the time before and after the abrupt change in temperature and precipitation. The sliding correlation analysis combined with SPEI also revealed that the precipitation failed to match it after the mutation with the temperature rising in the study area (*Fig. 1*). This phenomenon causes the decrease in relative humidity in the study area that enhances the standard precipitation evapotranspiration index.

The sliding correlation between atmospheric temperature and standard chronology (*Fig. 7*) clearly showed that responses to the mean temperature and precipitation are different across the study areas. These changes in precipitation presented a significant differential change in the sliding correlation between 1962 and 2017, the degree of response of JL to precipitation is insignificant, and the degree of response of LL to precipitation shows a significant correlation manifested in January and April–August of that year. Furthermore, significant differences exist between various elevations with minimum and maximum temperatures in some months, such as minimum temperatures

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in June and September of the year. This finding indicated that JL is more sensitive to minimum temperatures compared with LL and presents the same significant expression as the maximum temperature from April–September. The expression "differential effect" changed with some climatic factors before and after the abrupt temperature change. However, the primary change exists in different degrees of responses, and a significant shift from a positive or negative correlation to a negative or positive correlation was observed in some months.

Discussion

Analysis of the effect of temperature changes on radial growth

The significant correlation between the current radial growth of trees and global climate change is important at high elevations. We determine whether a significant difference exists in the "divergence" of the same tree species at various elevations to verify whether a significant difference exists in the radial growth of *L. kongboensis* due to the major shift in temperature. This study based on the Shergyla Mountain National Forest Park in Tibet examined the responses to radial-climatic factors. The analysis of the radial growth of *L. kongboensis* was combined with the M–K test and correlation analysis based on the confirmation of a significant "divergence phenomenon" between the radial growth and temperature of *L. kongboensis* to investigate the correlation between abrupt changes in temperature of *L. kongboensis*.

The correlation between radial growth of trees and temperature was significantly higher in the JL area than that in the LL area according to the correlation between radial growth of *L. kongboensis* with climate change before and after (*Fig. 5*). The limiting effect of minimum temperature on radial growth of trees in LL is significantly higher than that in JL, while studies on this point differ in other regions (Ponocná et al., 2018; Wang et al., 2022). A negative correlation is observed between minimum temperature and low elevation likely caused by warming temperatures. The temperature will continue to decline as elevation grows, but the radial growth of trees has progressively acclimated to the effects of low temperatures at high altitudes. Hence, the reaction between low temperatures is insensitive. By contrast, temperatures at lower elevations are more pleasant compared with those at higher elevations, and trees are more sensitive to changes in low temperatures during growth (Finley and Zhang, 2019; Barbeta et al., 2019; Dhyani et al., 2022; Zhao et al., 2017). The significance between radial growth of trees and temperature will increase significantly while the correlation with precipitation will decrease significantly as elevation increases. The comparison of before and after the abrupt change in temperature (*Fig. 6*) demonstrated that the correlation between the radial growth of trees concerning precipitation at high elevations is significantly enhanced by the increase in temperature and a significant lag exists between it and the precipitation in July of that year. Comparatively, the effect of increasing temperature on growth at high elevations gradually decreases, and the limiting factor for radial growth of trees at high elevations is still temperature; however, the correlation between radial growth of *L. kongboensis* and precipitation increases significantly compared with that before the temperature increase (Alvarez and Lidén et al., 2008; Körner and Paulsen, 2004).

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Divergent response of radial growth of different elevations of trees

As previously noted, trees of the same species express different responses to temperature changes between elevations, and correlations with temperature and precipitation are significantly different. The radial growth of *L. kongboensis* at LL was only positively correlated with the mean temperature in August of the year before the abrupt temperature change, but the correlation shifted to a positive correlation with the mean temperature in January of the year and a negative correlation with the mean temperature in July–September of the year with a significant "lag effect" after the abrupt temperature change (Yu et al., 2022). The maximum temperature was positively correlated with April of the current year before the temperature abrupt change which shifted to a negative correlation in February and March of the current year after the temperature abrupt change. Meanwhile, the correlation with November of the previous year was reduced. However, the correlation with precipitation changed from uncorrelated to negatively correlated with February and March precipitation and showed a significant lag with November precipitation. The relative humidity also shifted from a negative correlation with February to a negative correlation with May–July, and September with a significant lag.

This phenomenon is substantially more pronounced at higher elevations, especially between precipitation and minimum temperatures, compared with that at lower elevations (Chen et al., 2022). The temperature rises likely enhanced the climate for tree growth at high elevations for this response phenomenon. The sensitivity of trees to limiting climate temperature factors changes after an increase in temperature, such that climate factors that once inhibited tree growth can now promote growth. However, climatic factors that were initially positive for tree growth shifted to those that were negative during the course of tree growth at high elevations.

The tree's radial growth may be defined simply as growth, growth, and post growth (Wood et al., 2012; Callado et al., 2013). The tree's cells are highly responsive to the environmental temperature range and are on the verge of transforming from a dormant state to a developing state during the growth season (Corcuera et al., 2004; Esper et al., 2018). Moreover, factors, such as temperature and light in the environment, will activate the physiological activity inside tree cells and stimulate meristematic tissues (Kozlowski et al., 1962; Pérezdelis et al., 2011). Meanwhile, the increase in temperature will increase the cellular activity of trees in preparation for the formation of earlywood (Fonti et al., 2007; Matisons and Brūmelis, 2012). Therefore, the climate factor in the growth stage is the key stage that limits the formation of earlywood in trees and represents the majority of the tree rings; if the earlywood formation stage is disrupted, then the radial growth of trees in that year shows significant differential changes (Vieira et al., 2009; Alla and Camarero, 2012; Pérezdlis et al., 2018; Bergès et al., 2008).

The radial growth of the tree then transitions from the active state to the dormant state during the later growth season and dormancy. The transition from earlywood to latewood can be observed in this period. If environmental factors, such as temperature and precipitation, are favorable during the later stages of growth, then a long period of overgrowth of tree cells can be observed under the body microscope. The physiological activity of the tree declines in the later stages of growth and only the basic level of viability is retained. This period is important for the formation of latewood. Hence, the formation of latewood is influenced by the temperature and precipitation during the current year and the growth season (January–April) of the following year (Lebourgeois, 2000; Zhu et al., 2021). Increasing external temperatures will activate the transition from the dormant state to the

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growing state, whereas low temperatures will inhibit the transformation of trees during this period (Yu et al., 2011; Lo et al., 2010).

"Divergence problem" of radial growth of trees

L. kongboensis at the LL and JL stations exhibited a significant "divergence problem" after abrupt temperature changes likely because of the increase in temperature in recent decades (Ryan, 2010; Takahashi et al., 2003). The primary issue in this study was that the difference in elevation between LL and JL caused the same tree species to respond differently to various environmental factors after the temperature increase, with the response correlation to the minimum temperature demonstrating the most significant difference. The minimum temperature before and after the abrupt temperature change transformed from a negative correlation to a positive correlation for the radial growth of JL, but the radial growth of LL changed from no correlation to a positive significant association. This problem is caused by the change in the physiological activity of trees due to the elevation difference (Takahashi et al., 2003; Coomes and Allen, 2007; Rapp et al., 2012). The LL study site located at an elevation of 3100 m is the minimum elevation at which *L. kongboensis* can grow, and the natural environmental factors at this site are favorable; hence, the minimum temperature at this site fails to inhibit its growth significantly and temperature is not the primary factor limiting the radial growth of trees at low elevations (Zhu et al., 2021; Ryan, 2010). The minimum temperature reached the suitable threshold for tree growth with the increase in temperature after the temperature change (Lazarus et al., 2018; Lu et al., 2021). This phenomenon failed to limit the growth activity of trees and promoted the radial growth of *L. kongboensis* at "low altitudes." This finding was consistent with the recently proposed "threshold hypothesis" of Li et al., 2017. The JL research site is situated at an elevation of 3600 m, which is in the "high elevation" area where *L. kongboensis* is grown. Although the temperature in the study area may be beyond the suitable threshold (Li et al., 2017; Deslauriers et al., 2008), it showed a significant increase in the radial growth of *L. kongboensis* at JL because the climate increased and the minimum temperature also reached the suitable temperature for its growth at this time with the temperature change.

Furthermore, the radial growth of *L. kongboensis* in the JL study area also supports the "threshold hypothesis" because it changed from a positive correlation to a negative correlation with relative humidity. However, the occurrence of significant warming at high elevations promotes the growth of *L. kongboensis*, which fails to grow at the appropriate ambient temperature, when global temperatures rise as well as obtain suitable temperatures at "high elevations." However, promotive factors of *L. kongboensis*, which was previously growing in a favorable environment, may be transformed into limiting factors under the effect of abrupt temperature changes.

Conclusion

We hypothesized the different expressions of "divergent effects" between radial growth and temperature and precipitation in *L. kongboensis* grown at different elevations in the present experiment. A significant divergent response exists between precipitation and relative humidity in trees at high elevations. A significant divergent response between minimum temperature and precipitation is observed at low elevations. Our results revealed that the temperature changed abruptly in 1984 and *L. kongboensis* growing in different environments presents various levels of divergent responses to abrupt temperature changes. Trees at high and low elevations demonstrated a considerable divergence in reaction to precipitation and minimum air temperature both as a consequence of the temperature rise that resulted in the radial growth of trees caused by various environmental conditions. However, trees will readjust to this environmental disturbance with continued changes in temperature. Trees at higher altitudes will respond significantly to precipitation whereas minimum temperatures will become a new factor in restricting tree development for trees at lower elevations with the continued increase of temperatures.

Moreover, a correlation threshold exists between the radial growth of trees and the surrounding environment. The threshold will be a limiting factor for tree growth when the temperature or precipitation is below or above it. The threshold will be an important element for sustaining tree growth when the temperature or precipitation is within this threshold. The growth environment of *L. kongboensis* did not necessarily correlate with the geographical altitude, but 3100–3600 m was the suitable elevation for the growth of *L. kongboensis*. Hence, a high elevation range is physiologically suitable for *L. kongboensis* to facilitate its growth and development.

Local dominant species are often used as target species in studies on tree rings. Dominant species are less sensitive to temperature than endemic species despite offering significant advantages in reconstructing climate. The selection of climatological data and the development of experimental sample locations sometimes span hundreds of miles, and although trees lack sensitivity to low-frequency temperatures at small scales, they can still retain an outstanding response at broad sizes. We will attempt to mix dominant and endemic tree species and use the small scale to investigate the expression of radial growth of trees in the study area as a response to the external environment in future investigations.

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REFERENCES

[1] Alla, A. Q., Camarero, J. J. (2012): Contrasting responses of radial growth and wood anatomy to climate in a Mediterranean ring-porous oak: implications for its future persistence or why the variance matters more than the mean. – European Journal of Forest Research 131: 1537-1550. https://doi.org/10.1007/s10342-012-0621-x.

[2] Alvarez, R., Lidén, G. (2008): The effect of temperature variation on biomethanation at high altitude. – Bioresource Technology 99: 7278-7284. https://doi.org/10.1016/j.biortech.2007.12.055.

[3] Barbeta, A., Camarero, J. J., Sangüesa-Barreda, G., Muffler, L., Peñuelas, J. (2019): Contrasting effects of fog frequency on the radial growth of two tree species in a Mediterranean-temperate ecotone. – Agricultural and Forest Meteorology 264: 297-308.https://doi.org/10.1016/j.agrformet.2018.10.020.

[4] Bergès, L., Nepveu, G., Franc, A. (2008): Effects of ecological factors on radial growth and wood density components of sessile oak (Quercus petraea Liebl.) in Northern France. – Forest Ecology and Management 255: 567-579.https://doi.org/10.1016/j.foreco.2007.09.027.

[5] Callado, C. H., Roig, F. A., Tomazello-Filho, M., Barros, C. F. (2013): Cambial growth periodicity studies of South American woody species–a review. – IAWA journal 34: 213-230.http://dx.doi.org/10.1163/22941932-00000019.
[6] Chen, W., Ding, H., Li, J., Chen, K., Wang, H. (2022): Alpine treelines as ecological indicators of global climate change: Who has studied? What has been studied? – Ecological Informatics 101691. https://doi.org/10.1016/j.ecoinf.2022.101691.
[7] Comeau, V. M., Daniels, L. D., Knochenmus, G., Chavardès, R. D., Zeglen, S. (2019): Tree-rings reveal accelerated yellow-cedar decline with changes to winter climate after 1980. – Forests 10: 1085.https://doi.org/10.3390/f10121085.
[8] Coomes, D. A., Allen, R. B. (2007): Effects of size, competition and altitude on tree growth. – Journal of Ecology 95: 1084-1097. https://doi.org/10.1111/j.1365-2745.2007.01280.x.
[9] Corcuera, L., Camarero, J. J., Gil-Pelegrín, E. (2004): Effects of a severe drought on Quercus ilex radial growth and xylem anatomy. – Trees 18: 83-92. https://doi.org/10.1007/s00468-003-0284-9.
[10] Deslauriers, A., Rossi, S., Anfodillo, T., Saracino, A. (2008): Cambial phenology, wood formation and temperature thresholds in two contrasting years at high altitude in southern Italy. – Tree Physiology 28: 863-871.https://doi.org/10.1093/treephys/28.6.863.
[11] Dhyani, R., Bhattacharyya, A., Rawal, R. S., Joshi, R., Shekhar, M., Ranhotra, P. S. (2022): Is tree ring chronology of blue pine (Pinus wallichiana AB Jackson) prospective for summer drought reconstruction in the Western Himalaya? – Journal of Asian Earth Sciences 229: 105142.https://doi.org/10.1016/j.jseaes.2022.105142.
[12] Douglass, A. E. (1933): Tree growth and climatic cycles. – The Scientific Monthly 37: 481-495.https://www.jstor.org/stable/15538.
[13] Esper, J., George, S. S., Anchukaitis, K., D'Arrigo, R., Ljungqvist, F. C., Luterbacher, J., Schneider, L., Stoffel, M., Wilson, R., Büntgen, U. (2018): Large-scale, millennial-length temperature reconstructions from tree-rings. – Dendrochronologia 50: 81-90.https://doi.org/10.1016/j.dendro.2018.06.001.
[14] Finley, K., Zhang, J. (2019): Climate effect on ponderosa pine radial growth varies with tree density and shrub removal. – Forests 10: 477.https://doi.org/10.3390/f10060477.
[15] Fonti, P., Solomonoff, N., García-González, I. (2007): Earlywood vessels of Castanea sativa record temperature before their formation. – New Phytologist 173: 562-570.https://doi.org/10.1111/j.1469-8137.2006.01945.x.
[16] Fritts, H. C. (1971): Dendroclimatology and dendroecology. – Quaternary Research 1: 419-449.https://doi.org/10.1016/0033-5894(71)90057-3.
[17] Gao, H., Liu, L. J., Fang, J. P. (2020): Change pattern of forest community along an altitude gradient in Sejila Mountain, Tibet, China. – Journal of Guangxi Normal University (Natural Science Edition) 38: 122-130. https://doi.org/10.16088/j.issn.1001-6600.2020.06.014.
[18] Guo, Q., Li, H., Zheng, W. et al. (2022): Analysis of genetic diversity and prediction of Larix species distribution in the Qinghai–Tibet Plateau, China. – J. For. Res. https://doi.org/10.1007/s11676-022-01513-1.
[19] Jevšenak, J., Tychkov, I., Gričar, J., Levanič, T., Tumajer, J., Prislan, P., Arnič, D., Popkova, M., Shishov, V. V. (2021): Growth-limiting factors and climate response variability in Norway spruce (Picea abie.) along an elevation and precipitation gradients in Slovenia. – International Journal of Biometeorology 65: 311-324. https://doi.org/10.1007/s00484-020-02033-5.
[20] Jing, S., Solhøy, T., Huifu, W., Vollan, T. I., Rumei, X. (2005): Differences in soil arthropod communities along a high altitude gradient at Shergyla Mountain, Tibet, China. – Arctic, Antarctic, and Alpine Research 37: 261-266. https://www.jstor.org/stable/4139085.

[21] Körner, C., Paulsen, J. (2004): A world-wide study of high altitude treeline temperatures. – Journal of Biogeography 31: 713-732. https://doi.org/10.1111/j.1365-2699.2003.01043.x.
[22] Kozlowski, T., Winget, C., Torrie, J. (1962): Daily radial growth of oak in relation to maximum and minimum temperature. – Botanical Gazette 124: 9-17. https://doi.org/10.1086/336167.
[23] Lazarus, B. E., Castanha, C., Germino, M. J., Kueppers, L. M., Moyes, A. B. (2018): Growth strategies and threshold responses to water deficit modulate effects of warming on tree seedlings from forest to alpine. – Journal of Ecology 106: 571-585. https://doi.org/10.1111/1365-2745.12837.
[24] Lebourgeois, F. (2000): Climatic signals in earlywood, latewood and total ring width of Corsican pine from western France. – Annals of Forest Science 57: 155-164. https://doi.org/10.1051/forest:2000166.
[25] Li, X., Liang, E., Gričar, J., Rossi, S., Čufar, K., Ellison, A. M. (2017): Critical minimum temperature limits xylogenesis and maintains treelines on the southeastern Tibetan Plateau. – Science Bulletin 62: 804-812. https://doi.org/10.1016/j.scib.2017.04.025.
[26] Lo, Y.-H., Blanco, J. A., Seely, B., Welham, C., Kimmins, J. H. (2010): Relationships between climate and tree radial growth in interior British Columbia, Canada. – Forest Ecology and Management 259: 932-942. https://doi.org/10.1016/j.foreco.2009.11.033.
[27] Lu, X., Camarero, J. J., Liang, E. (2021): Threshold Responses of Juniper Tree Growth and Regeneration to Climate Warming and Drought Stress at Alpine Treeline. – Trees 35: 1081-1083. https://doi.org/10.1007/s00468-021-02135-6.
[28] Lun, L. (2018): Meteorological observation data from the integrated observation and research station of the alpine environment in Southeast Tibet (2007-2017). – In: National Tibetan Plateau Data. http://dx.doi.org/10.11888/AtmosphericPhysics.tpe.68.db.
[29] Luo, Y., Yang, D., O'Connor, P., Wu, T., Ma, W., Xu, L., Guo, R., Lin, J. (2022): Dynamic characteristics and synergistic effects of ecosystem services under climate change scenarios on the Qinghai–Tibet Plateau. – Scientific Reports 12: 1-15. https://doi.org/10.1038/s41598-022-06350-0.
[30] Marques, I. G., Campelo, F., Rivaes, R., Albuquerque, A., Ferreira, M., Rodríguez-González, P. (2018): Tree rings reveal long-term changes in growth resilience in Southern European riparian forests. – Dendrochronologia 52: 167-176. https://doi.org/10.1016/j.dendro.2018.10.009.
[31] Matisons, R., Brūmelis, G. (2012): Influence of climate on tree-ring and earlywood vessel formation in Quercus robur in Latvia. – Trees 26: 1251-1266. https://doi.org/10.1007/s00468-012-0701-z.
[32] Meng, S., Fu, X., Zhao, B., Dai, X., Li, Q., Yang, F., Kou, L., Wang, H. (2021): Intra-annual radial growth and its climate response for Masson pine and Chinese fir in subtropical China. – Trees 35: 1817-1830. https://doi.org/10.1007/s00468-021-02152-5.
[33] Natalini, F., Correia, A. C., Vázquez-Piqué, J., Alejano, R. (2015): Tree rings reflect growth adjustments and enhanced synchrony among sites in Iberian stone pine (Pinus pine.) under climate change. – Annals of Forest Science 72: 1023-1033. https://doi.org/10.1007/s13595-015-0521-6.
[34] Nie, X. Q., Wang, D., Zhou, G.Y., Xiong, F., Du, Y. G. (2021): Soil microbial biomass carbon, nitrogen, phosphorus and their stoichiometric characteristics in alpine wetlands in the Three Rivers Sources Region. – Chinese Journal of Plant Ecology 45 996-1005. https://doi.org/10.17521/cjpe.2021.0113.
[35] Pandey, J., Sigdel, S. R., Lu, X., Salerno, F., Dawadi, B., Liang, E., Camarero, J. J. (2020): Early growing-season precipitation drives radial growth of alpine juniper shrubs in the central Himalayas. – Geografiska Annaler: Series A, Physical Geography 102: 317-330. https://doi.org/10.1080/04353676.2020.1761097.
[36] Pérez-de-Lis, G., García-González, I., Rozas, V., Arévalo, J. R. (2011): Effects of thinning intensity on radial growth patterns and temperature sensitivity in Pinus

canariensis afforestations on Tenerife Island, Spain. – Annals of Forest Science 68: 1093-1104. https://doi.org/10.1007/s13595-011-0125-8.
[37] Pérez-de-Lis, G., Rozas, V., Vázquez-Ruiz, R. A., García-González, I. (2018): Do ring-porous oaks prioritize earlywood vessel efficiency over safety? Environmental effects on vessel diameter and tyloses formation. – Agricultural and Forest Meteorology 248: 205-214. https://doi.org/10.1016/j.agrformet.2017.09.022.
[38] Ponocná, T., Chuman, T., Rydval, M., Urban, G., Migała, K., Treml, V. (2018): Deviations of treeline Norway spruce radial growth from summer temperatures in East-Central Europe. – Agricultural and Forest Meteorology 253: 62-70. https://doi.org/10.1016/j.agrformet.2018.02.001.
[39] Rahman, M., Islam, M., Braeuning, A. (2018): Tree radial growth is projected to decline in South Asian moist forest trees under climate change. – Global and Planetary Change 170: 106-119. https://doi.org/10.1016/j.gloplacha.2018.08.008.
[40] Rapp, J. M., Silman, M. R., Clark, J. S., Girardin, C. A., Galiano, D., Tito, R. (2012): Intra-and interspecific tree growth across a long altitudinal gradient in the Peruvian Andes. – Ecology 93: 2061-2072. https://doi.org/10.1890/11-1725.1.
[41] Rodriguez-Caton, M., Andreu-Hayles, L., Morales, M. S., Daux, V., Christie, D. A., Coopman, R. E., Alvarez, C., Rao, M. P., Aliste, D., Flores, F. (2021): Different climate sensitivity for radial growth, but uniform for tree-ring stable isotopes along an aridity gradient in Polylepis tarapacana, the world's highest elevation tree species. – Tree Physiology 41: 1353-1371. https://doi.org/10.1093/treephys/tpab021.
[42] Ryan, M. G. (2010): Temperature and tree growth. – Tree Physiology 30: 667-668. https://doi.org/10.1093/treephys/tpq033.
[43] Shao, J.-L., Lai, B., Jiang, W., Wang, J.-T., Hong, Y.-H., Chen, F.-B., Tan, S.-Q., Guo, L.-X. (2019): Diversity and co-occurrence patterns of soil bacterial and fungal communities of Chinese Cordyceps habitats at Shergyla Mountain, Tibet: implications for the occurrence. – Microorganisms 7: 284. https://doi.org/10.3390/microorganisms7090284.
[44] Soulé, P. T., Knapp, P. A., Maxwell, J. T., Mitchell, T. J. (2021): A comparison of the climate response of longleaf pine (Pinus palustris Mill.) trees among standardized measures of earlywood, latewood, adjusted latewood, and totalwood radial growth. – Trees 35: 1065-1074. https://doi.org/10.1007/s00468-021-02093-z.
[45] Takahashi, K., Azuma, H., Yasue, K. (2003): Effects of climate on the radial growth of tree species in the upper and lower distribution limits of an altitudinal ecotone on Mount Norikura, central Japan. – Ecological Research 18: 549-558. https://doi.org/10.1046/j.1440-1703.2003.00577.x.
[46] Tang, G. Q., Liu, Y. T., Gao, W. K., Wang, Y. H., Song, T., Cheng, M. T., Wang, Y. S. (2022): Alert to the migration of air pollution and carbon emission to northwest China. – Bulletin of Chinese Academy of Sciences 37: 230-237. https://doi.org/10.16418/j.issn.1000-3045.20211019001.
[47] Tei, S., Sugimoto, A., Yonenobu, H., Ohta, T., Maximov, T. C. (2014): Growth and physiological responses of larch trees to climate changes deduced from tree-ring widths and δ13C at two forest sites in eastern Siberia. – Polar Science 8: 183-195. https://doi.org/10.1016/j.polar.2013.12.002.
[48] Truettner, C., Anderegg, W. R., Biondi, F., Koch, G. W., Ogle, K., Schwalm, C., Litvak, M. E., Shaw, J. D., Ziaco, E. (2018): Conifer radial growth response to recent seasonal warming and drought from the southwestern USA. – Forest Ecology and Management 418: 55-62. https://doi.org/10.1016/j.foreco.2018.01.044.
[49] Tso, C.-H. M., Monteith, D., Scott, T., Watson, H., Dodd, B., Pereira, M. G., Henrys, P., Hollaway, M., Rennie, S., Lowther, A. (2022): The evolving role of weather types on rainfall chemistry under large reductions in pollutant emissions. – Environmental Pollution 299: 118905. https://doi.org/10.1016/j.envpol.2022.118905.

[50] Vieira, J., Campelo, F., Nabais, C. (2009): Age-dependent responses of tree-ring growth and intra-annual density fluctuations of Pinus pinaster to Mediterranean climate. – Trees 23: 257-265. https://doi.org/10.1007/s00468-008-0273-0.
[51] Wang, J., Li, S., Guo, Y., Yang, Q., Ren, R., Han, Y. (2022): Responses of Larix principis-rupprechtii Radial Growth to Climatic Factors at Different Elevations on Guancen Mountain, North-Central China. – Forests 13: 99. https://doi.org/10.3390/f13010099.
[52] Wood, K. A., Stillman, R. A., Clarke, R. T., Daunt, F., O'Hare, M. T. (2012): Understanding plant community responses to combinations of biotic and abiotic factors in different phases of the plant growth cycle. – PloS One 7: e49824. https://doi.org/10.1371/journal.pone.0049824.
[53] Xu, J., Jing, B., Zhang, K., Cui, Y., Malkinson, D., Kopel, D., Song, K., Da, L. (2017): Heavy metal contamination of soil and tree-ring in urban forest around highway in Shanghai, China. – Human and Ecological Risk Assessment: An International Journal 23: 1745-1762. https://doi.org/10.1080/10807039.2017.1340826.
[54] Xue, R. H., Jiao, L., Liu, X. P. (2021): Evaluation of the stability of the radial growth of Larix sibirica at different altitudes in response to climate change in the Altai Mountains, Xinjiang. – Chinese Journal of Ecology 40 1275-1284.https://doi.org/10.13292/j.1000-4890.202105.021.
[55] Yu, D., Wang, Q., Wang, Y., Zhou, W., Ding, H., Fang, X., Jiang, S., Dai, L. (2011): Climatic effects on radial growth of major tree species on Changbai Mountain. – Annals of Forest Science 68: 921-933. https://doi.org/10.1007/s13595-011-0098-7.
[56] Yu, D. S., Lu, J., Zhang, M., Zhang, X. S. (2022): Response of radial growth of Larix griffithii to temperature and precipitation fluctuation in Tibet Shergyla Mountain. – Forest Research 35: 1-9.
[57] Zhang, Y., Yin, D. C., Tian, K., Xiao, D. R., Sun, M., Wang, H., Zhang, W. G. (2017): Response of radial growth of Larix potaninii var. macrocarpa to climate change at upper distributional limits on Northwestern Yunnan Plateau, China. – Chinese Journal of Applied Ecology 2017: 28 2805-2812.https://doi.org/10.13287/j.1001-9332.201709.011.
[58] Zhao, Y., Shi, J., Shi, S., Yu, J., Lu, H. (2017): Tree-ring latewood width based July–August SPEI reconstruction in South China since 1888 and its possible connection with ENSO. – Journal of Meteorological Research 31: 39-48. https://doi.org/10.1007/s13351-017-6096-4.
[59] Zhu, L., Liu, S., Arzac, A., Cooper, D. J., Jin, Y., Yuan, D., Zhu, Y., Zhang, X., Li, Z., Zhang, Y. (2021): Different response of earlywood vessel features of Fraxinus mandshurica to rapid warming in warm-dry and cold-wet areas. – Agricultural and Forest Meteorology 307: 108523.https://doi.org/10.1016/j.agrformet.2021.108523.

APPENDIX

Appendix 1. *Photo of core sample*

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