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Radial growth response of *Pinus Yunnanensis* to climate in high mountain forests of northwestern Yunnan, southwestern China

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Understanding the relationship between tree growth and environmental conditions is essential to elucidating the impact of global climate change on forest ecosystems. We used the dendrochronology method to examine the growth sensitivity of a typical conifer to climate change in mountain forests of Central Hengduan Mountain. The study involved the establishment of tree ring width chronologies of *Pinus yunnanensis* in both Haba Snow Mountain (HB) and Yulong Snow Mountain (YL) in northwestern Yunnan, enabling the detection of the relationship between its radial growth and climates, i.e., monthly total precipitation, monthly temperatures (average minimum, mean and maximum) and monthly Palmer Drought Severity Index (PDSI). Response function and redundancy analysis (RDA) were used to identify correlations between climate variables and radial growth, and moving interval analysis was applied to determine the stability of climate-growth relationship. The findings demonstrated that the growth of *P. yunnanensis* had similar response patterns to climate change at two sites, exhibiting growth synchronization and common signals. Specifically, the radial growth of *P. yunnanensis* was negatively correlated with May temperature, while temperature in current October significantly promoted radial growth. Precipitation in June was the common climate variable with inverse effects between two sites, with positive impacts on YL and negative impacts on HB. The results of moving interval analysis were consistent with response function and RDA, presenting significant correlations in many years for those climatic variables significantly affecting tree growth. Stability analysis also revealed that the climate-growth relationship could fluctuate over a small range of time scales, induced by an abrupt change in climate. A forecast of strengthen in growth of *P. yunnanensis* forests was expected, since increases in precipitation and temperature of most months would benefit tree growth, and negative impacts of May temperature would be offset by the increase of precipitation in the corresponding month. These results could provide a basis for developing sustainable strategies of forest management under the climate change.

KEYWORDS

tree ring, conifer, dendroclimatology, climate change, climate-growth relationships

1 Introduction

Global surface temperature will continue to increase until at least mid-century. Global warming will exceed 1.5°C to 2°C during the 21st century unless deep reduction measures of CO_2 and other greenhouse gas emissions will be carried out in the coming decades (IPCC, 2021). In southwestern China, the climate has been warming and drying, with a tendency of intensification since the beginning of the 21st century (Su et al., 2014). Climate change has a massive impact on the structure and function of terrestrial ecosystems. For forest ecosystems, the largest component of the terrestrial ecosystem, climate change has greatly influenced its composition, structure, productivity, carbon storage capability, and ecological function (Zhang et al., 2017; Fan et al., 2019). Tree radial growth is sensitive to climate variation and mainly affected by climate factors, thus, a better understanding of climate effects on tree growth will help predict growth dynamics of forests under global climate change.

Climate warming is expected to enhance tree growth at alpine treelines (Camarero et al., 2021). Nevertheless, these positive influences need to be considered alongside water availability (Martínez-Vilalta et al., 2008), as high temperatures may lead to an increase in the frequency and intensity of droughts. If water availability is insufficient, the impact of drought stress on tree physiological processes will worsen, and consequently lead to a reduction of tree growth (Aber et al., 2001). Recent studies have revealed that droughts widely affected tree and forests growth over the world and even determined the survival of trees. For instance, a study found that consecutive hotter droughts posed a threat to forests under climate change in Central European floodplain forests, even with comparably high levels of water supply (Schnabel et al., 2022). Years with more intense drought corresponded with larger growth reductions and increased tree mortality rates in California forests, North America (Young et al., 2017; Bohner and Diez, 2021). Studies in Tibetan Plateau have shown that water deficit was the main factor controlling the resistance of juniper trees and higher drought frequency caused the decline of junipers' growth, which was due to a lower tolerance to extreme drought events (Fang et al., 2021). In South America, predicted increases in drought frequency and intensity can have negative consequences for the functioning of the Amazon Forest (Van Passel et al., 2022).

Tree ring width is commonly used as a tree ring parameter and a measure of tree increment, which has contributed to the largest proportion of dendroclimatological research worldwide (He et al., 2019). Due to its precision as a proxy of recording climate information up to the millennium scale (Shen et al., 2020), it has been a useful tool in evaluating growth sensitivity to climate change and assessing the impact of future climate change on the radial growth of tree species and forests (Huang et al., 2010).

The Central Hengduan Mountains (CHM) is located in southeastern margin of Tibetan Plateau, which is a sensitive region to global climate change (Zhang et al., 2020). It is rich in biodiversity and covered by extensive forests composed of various species, covering their altitude distributional range and forming different treeline types. Therefore, the area is considered an excellent location to conduct a dendroclimatology study (Fan et al., 2009). Many efforts have been made to reconstruct historical climate and to find key climate factors affecting tree growth by using tree ring data of typical coniferous tree species in CHM, such as for *Abies georgei* (Fan et al., 2009; Liang et al., 2010; Panthi et al., 2018), *Larix potaninii* (Zhang et al., 2017, 2020), *Picea brachytyla* (Fan et al., 2008; Li et al., 2012; Yue et al., 2022), *Picea likiangensis* (Wang et al., 2018; Yu et al., 2018; Du et al., 2020), and *Tsuga dumosa* (Guo G. et al., 2009; Li et al., 2011; Aryal et al., 2020). These studies found that tree radial growth was influenced by both temperature and precipitation, but the growth response pattern was depended on species characteristics and site conditions. These studies provide an opportunity to understand climate-growth relationships for tree species and forests in high-altitude areas, and their connection to large-scale climate models (He et al., 2019).

Pinus yunnanensis forests are mainly distributed in Yunnan-Guizhou Plateau and in the southeastern edge of the Tibetan Plateau, and are important timber forests in southwestern China (Fu et al., 1999). *P. yunnanensis* is a shade-intolerant and deep-rooted coniferous species growing at altitudes between 1800 to 3,200 m a.s.l. in CHM (Deng et al., 2014; Shen et al., 2020). The species has strong adaptability to arid climate and barren soil, with red soil as the representative soil type. It grows best on well-drained north slopes with adequate light. The concurrent climate conditions in CHM are consistent with the climate background of global warming, which makes this typical species particularly interesting for studying the growth response to climate change. Tree ring studies of *P. yunnanensis* have been carried out at high (Yang et al., 2018, 2022), medium (Shen et al., 2020), and low altitudes in southwestern China (Sun et al., 2020). However, its growth responses to climate change in CHM is not well understood.

In this paper, we utilized dendrochronology methods to study the relationship between the radial growth of *P. yunnanensis* and climate by establishing tree ring width chronologies and detecting its growth response to climate factors on Haba Snow Mountain (HB) and Yulong Snow Mountain (YL) in CHM. We aim to (1) identify the critical climate factors affecting the growth of *P. yunnanensis* in the area, and (2) analyze the temporal stability of climate-growth relationships to determine whether the growth response to annual climate factors is smooth over time. It was hypothesized that temperature and precipitation interacted temporally, and negative impacts of temperature on growth were expected in dry periods. Furthermore, we explored the impact of future climate change on *P. yunnanensis* forests growth based on climate-growth relationships results and climate models.

2 Materials and methods

2.1 Study area

HB with the peak of 5,396 m a.s.l. and YL with the peak of 5,596 m a.s.l. are two typical snow-capped mountains in the Central Hengduan Mountain (CHM), separated by the Jinsha River (Figure 1). Different vegetation types are formed along the altitudinal gradient in CHM. The dry valleys are usually covered by scrublands. Warm-temperate coniferous forests, dominated by *P. yunnanensis* and *Pinus armandii*, are mainly distributed at altitudes between 1,000 m a.s.l. and 3,300 m a.s.l. *Pinus densata* is a dominant species at altitudes of 2,600 to 3,500 m a.s.l. on the southern slope. Cold-temperate coniferous forests are dominated by spruce (*P. brachytyla*, *P. likiangensis*), fir (*A. georgei*, *Abies forrestii*) and larch species (*L. potaninii*), at elevations ranging from 3,000 m a.s.l. to 4,200 m a.s.l. (Fan et al., 2009).

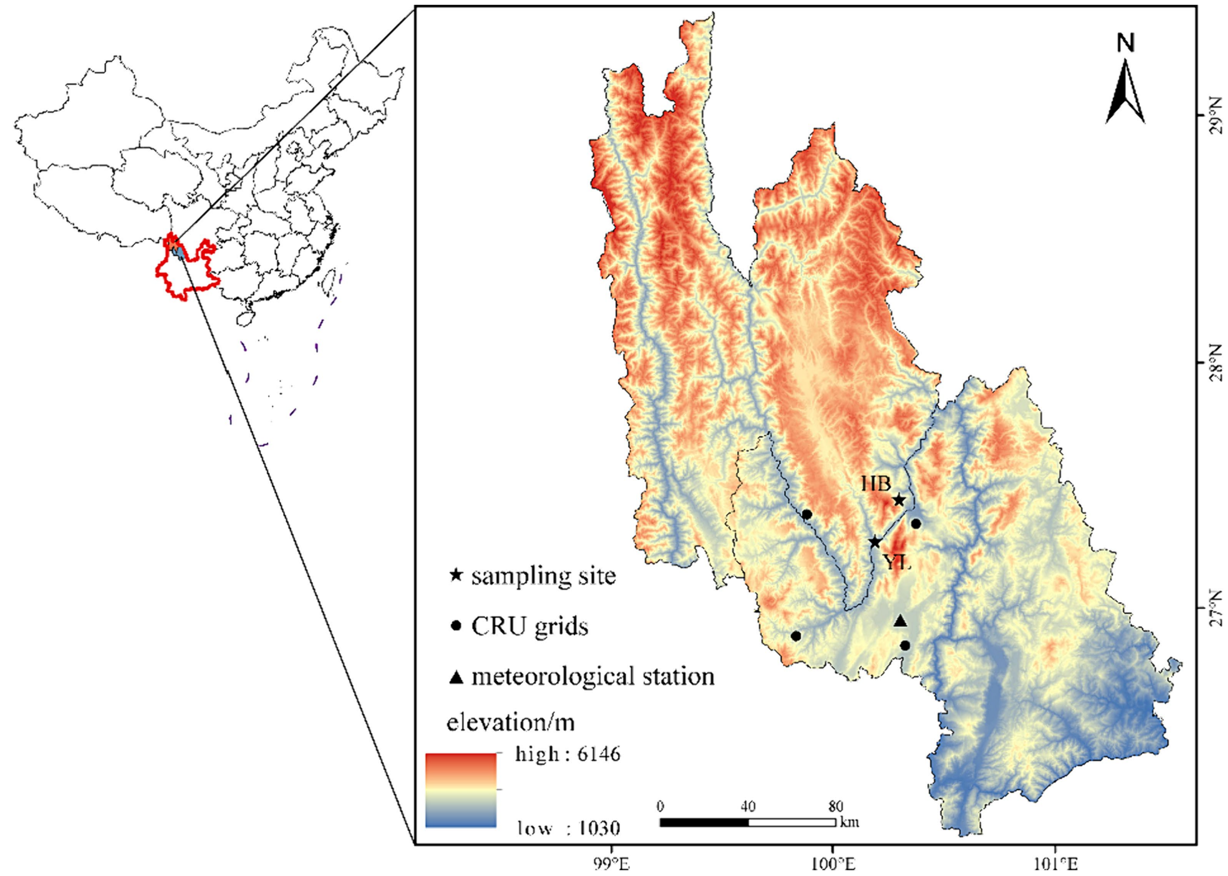

FIGURE 1
The location of sampling sites and meteorological station. HB: Haba Snow Mountain; YL: Yulong Snow Mountain; the same below.

Although vegetation types along the altitudinal gradient were similar in both HB and YL, the distribution range of *P. yunnanensis* was a bit different. The species is mainly distributed from 2000 m a.s.l. to 3,500 m a.s.l. in HB, while the distribution of *P. yunnanensis* in YL ranged from 2000 m a.s.l. to 3,000 m a.s.l. In HB, the soil texture is predominantly loamy, distributed from 1800 to 3,450 m a.s.l., transitioning from red soils to yellow and then brown soils. Above 3,900 m a.s.l., podzolic soil and meadow soil prevail. In YL, the soil texture is dominated by loam and clay, with a gradual transition from clay and loamy clay to sandy clay, sandy loam, and loam as the altitude increases from low to high.

The climate in CHM is strongly influenced by the southeast monsoon and southwest monsoon, with the monsoon climate characteristics of simultaneous rain and heat, and distinct dry and wet seasons. According to the meteorological data (1951–2021) of Lijiang meteorological station (26°51′N, 100°13′E, 2380.9 m a.s.l., Figure 2), annual mean temperature was 12.97°C, while annual maximum temperature (23.92°C) and annual minimum temperature (−0.11°C) appeared in June and January, respectively. The annual total precipitation was 988.93 mm, mainly occurring in summer, as the precipitation from June to September accounted for 75% of the total precipitation. Over the last three decades, the climate of the study area has been characterized by noticeable warming and drying, with a significant increasing trend in temperature (particularly during the period from 1990 to 2016) and a decreasing trend in Palmer Drought Severity Index (PDSI) between 1951 and 2021, while precipitation did not show a significant decreasing trend (Figure 3).

2.2 Tree-ring sampling and chronology development

We sampled mature and healthy trees without insect damage at undisturbed forest communities at two adjacent sites with similar climate conditions and growth environments (Table 1). The cores were drilled at the trees' breast height (1.3 m) with a 5.15-mm-diameter increment borer, one or two cores were extracted per tree from the opposite direction parallel to the contour to avoid growth reaction to the slope. Obtained cores were labelled and placed in plastic straws. In the laboratory, the cores were put into wooden tanks by using white latex and tape. The samples were polished by sandpaper with gradually finer particle sizes (200 mesh to 1,000 mesh) until the growth rings were visible. Then, the cores were visual cross-dating under a microscope and scanned by EPSON (Expression11000XL) scanner. The scanner parameters were set to 24-bit full-color professional mode image types, with a resolution of 2000 dpi. The dated cores were measured using the CDendro and CooRecorder ver. 9.8.1 software at a precision of 0.001 mm to obtain the ring widths. Furthermore, the results of cross-dating were examined by the COFECHA program (Holmes, 1983), and those cores with inadequate quality were

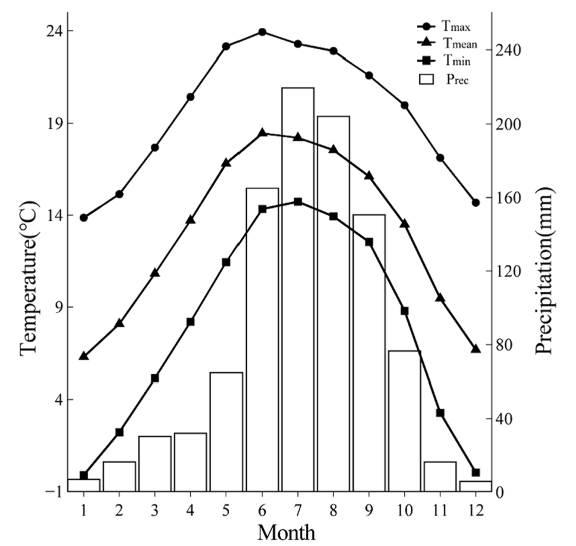

FIGURE 2
The monthly climatic characteristics at Lijiang Meteorological Station (1951–2021). Prec, monthly total precipitation; T_{min}, monthly mean minimum temperature; T_{mean}, monthly mean temperature; T_{max}, monthly mean maximum temperature.

removed based on the testing results. Ultimately, 62 trees from 112 cores remained for the further analysis.

To remove the growth trend caused by genetic factors or individual interference while preserving more climate signals, a negative-exponential curve function was applied to standardize the ring width series. Residual chronologies (Figure 4) were developed after autoregressive modelling performed on per standardized series to remove potential autocorrelation and retain high-frequency climate change. Further, all residual series were averaged on a site-by-site basis utilizing the bi-weight robust mean (Cook, 1985), to minimize the influence of outliers. All procedures were executed using the ARSTAN Program (Cook, 1985) and two residual chronologies were generated with chronological eigenvalue (Table 2), including mean sensitivity (MS), signal-to-noise ratio (SNR), standard deviation (SD), and expressed population signal (EPS), etc.

The MS quantifies the degree of inter-annual variation in ring width, serving as an indicator of the sensitivity of tree growth to climate change. A higher value indicates a greater inter-annual variation in ring width, suggesting that the trees are highly responsive to environmental changes. The SNR serves as an indicator of the proportion of climatic signals to non-climatic noise within the ring width data. A high SNR signifies that the ring-width data contains a richer climatic information. The SD is a statistical measure that assesses the dispersion of tree ring width data, reflecting the variation in ring width across different growth years. The EPS is a statistical metric that assesses the representativeness of a sample. A high value of EPS means that the sample data are well represented and can be used to infer growth and climate change in broader regions.

2.3 Climate data

Monthly mean maximum temperature (T_{max}), monthly mean temperature (T_{mean}), and monthly mean minimum temperature (T_{min}), sourced from the neareast Lijiang Meteorological Station (26°50′N, 100°13′E, 2,382 m a.s.l), were acquired through the National Oceanic and Atmospheric Administration (NOAA).[1] Precipitation data were obtained from the Climatic Research Unit (CRU TS v. 4.07; https://crudata.uea.ac.uk/cru/data/hrg) at a resolution of 0.5° × 0.5° (Harris et al., 2020). The PDSI is a comprehensive meteorological drought index that considers precipitation, temperature, evapotranspiration, and drought duration (Alley, 1985). The PDSI data was extracted from the monthly data set compiled by the global CRU grids[2] at 0.5° × 0.5° spatial resolution (Dunn et al., 2022). Its index ranges from −4 (indicating extremely dry conditions) to +4 (indicating extremely wet conditions), where a smaller value represents a more severe relative drought.

2.4 Data analysis

To capture the lag effect of climate on tree radial growth (Fritts et al., 1965), each tree ring was paired with 14 months of climate data spanning from the previous year's September through the following October. The climate timeseries interval was from 1987 to 2017 for the data analysis. Five climate variables were selected for analyzing relation to tree radial growth, including T_{mean}, T_{max}, T_{min}, the monthly total precipitation, and PDSI.

The response function was applied to analyze correlations between climate variables and chronologies by using DendroClim2002 (Biondi and Waikul, 2004). The coefficients of the response function are multivariate estimates from a principal component regression model (Morzuch and Ruark, 1991) and the method solves the inter-correlation problems among climatic variables (Fritts et al., 1971). To further identify common climate variables affecting the radial growth of *P. yunnanensis*, the redundancy analysis (RDA) was also conducted using CANOCO 5.0 software. RDA is the canonical form of principal component analysis (PCA) and constitutes the direct extension of multiple regressions applied to multivariate data (Legendre and Legendre, 1998). In RDA, the ordination axes are constrained to be linear combinations of supplied environmental variables (ter Braak, 1994), and it is an effective method in quantifying the relationship between tree-ring width and climate variables (Girardin et al., 2004; Drobyshev et al., 2013; Zhang et al., 2020). Like the response function, T_{mean}, T_{max}, T_{min}, the monthly total precipitation, and PDSI were selected for RDA. Following a Monte Carlo permutation test involving 999 random permutations, only those climate variables showing significant correlations ($p < 0.05$) with the two residual chronologies were presented in the RDA.

For tracing the dynamic relationship over time between the annual ring width index and climate, the Moving Forward method (with a window of 36 years) in the Evolutionary and Moving Response and Correlation module of DendroClim 2002 software was also applied to calculate temporal stability of relationships between chronologies and climate variables. The Special Report on Emissions Scenarios (SRES) B2 scenario was considered as future changes in temperature and precipitation, it was published by the Intergovernmental Panel on Climate Change to provide an assessment

1 https://www.ncei.noaa.gov/maps-and-geospatial-products
2 https://crudata.uea.ac.uk/cru/data/drought

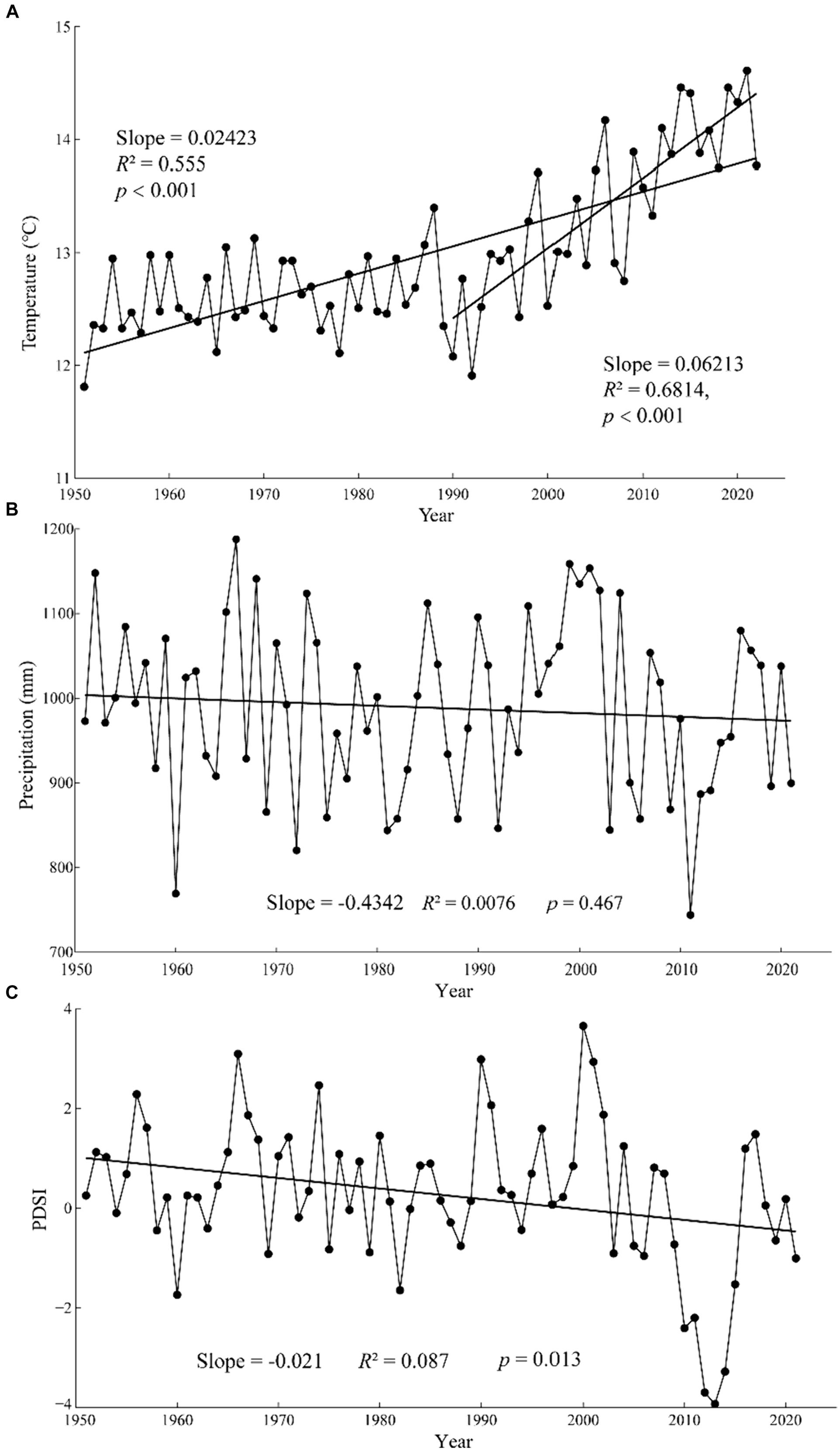

FIGURE 3
Annual trends of mean temperature **(A)**, precipitation **(B)** and Palmer Drought Severity Index (PDSI) **(C)** at Lijiang Meteorological Station (1951–2021).

TABLE 1 Sampling sites information.

Sampling site	Longitude	Latitude	Altitude (m)	No. (trees/cores)
HB	100°09′50.18″	27°20′34.02″	3,214	32/62
YL	100°04′16″	27°09′48″	2,935	30/56

HB, Haba Snow Mountain; YL, Yulong Snow Mountain; the same below.

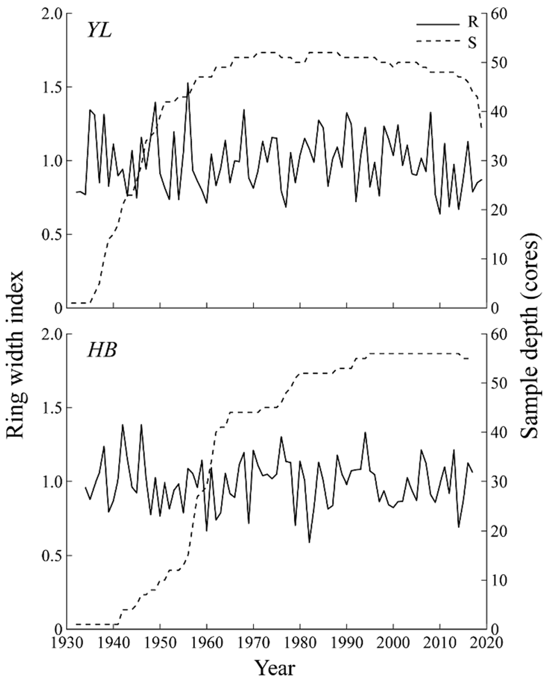

FIGURE 4
Residual chronologies of tree ring width for two sampling sites. R, ring width index; S, sample depth.

of the climate change. The graphs were plotted using the ggplot2 program package in R.

3 Results

3.1 Tree-ring chronologies

Both residual chronologies with high values of SNR and variance in first eigenvector contained large climate information (Table 2). Tree growing in YL with greater MS and SD showed higher interannual fluctuations than those in HB (Table 2). The high EPS (>0.85) confirmed that the sampled population for each site was well-represented, and two residual chronologies could reflect the overall growth characteristics of *P. yunnanensis* in the study area and then the chronologies could be applied to conduct correlation analysis with climate variables.

3.2 Climate-growth relationship

We showed correlations between radial growth and climate variables in Figure 5. In HB, the radial growth of *P. yunnanensis* was

TABLE 2 Statistics of tree ring width residual chronologies.

Statistic characters	HB	YL
Sample depth (trees/cores)	32/56	30/56
Time span (A.D)	1932–2017	1931–2019
Common interval analysis	1966–2016	
Mean sensitivity (MS)	0.18	0.24
Standard deviation (SD)	0.16	0.20
Signal-to-noise ratio (SNR)	20.67	21.10
Expressed population signal (EPS)	0.95	0.96
Variance in first eigenvector (%)	36.23	39.54

significantly associated with T_{max} in May and precipitation in February, by showing negative and positive correlations, respectively. In addition, PDSI in the previous September negatively affected *P. yunnanensis* growth. In YL, the radial growth was significantly and negatively correlated with May and June temperatures (both T_{mean} and T_{max}), and significantly and positively correlated with T_{mean} and T_{min} of the current October. While *P. yunnanensis* radial growth was found to be positively correlated with precipitation in May and June, and previous October. For PDSI, significant and positive correlations were found in June and July.

3.3 Redundancy analysis

The results of RDA (Figure 6) revealed that three climate variables significantly affected the radial growth of *P. yunnanensis*. Specifically, May T_{mean}, current October T_{mean}, and June precipitation explained 17.9, 6.7, and 4.7% of the radial growth, respectively. The first axis and the second axis accounted for 24.49 and 4.85% of the response variables, respectively. May T_{mean} exerted the most considerable influence on radial growth with negative impacts at both sites, while current October T_{mean} positively affected the radial growth. June precipitation presented inverse impacts on tree growth at two sites, by showing negative and positive influences in HB and YL, respectively.

3.4 Dynamic relationships analysis

The moving response analysis results (Figures 7A,C,E) showed that the growth response of *P. yunnanensis* to precipitation in May remained relatively stable in HB, by showing positive correlations over the decade with significant periods between 1987 and 1999. The negative response to May temperature reached a significant level before 2000 ($p < 0.05$) and then weakened. The drought condition in previous September was likely to affect *P. yunnanensis* growth, as the negative influences of PDSI strengthened in recent 20 years.

In YL, the response of *P. yunnanensis* to precipitation (positive) and temperature (negative) in current May, temperature in current October (positive), and PDSI (negative) in current October were stable, by showing significant correlations at many years. For current June, the negative impacts of temperature and positive effects of precipitation on tree growth were enhanced after 1992. In Addition, the positive response to PDSI in current June and July fluctuated due

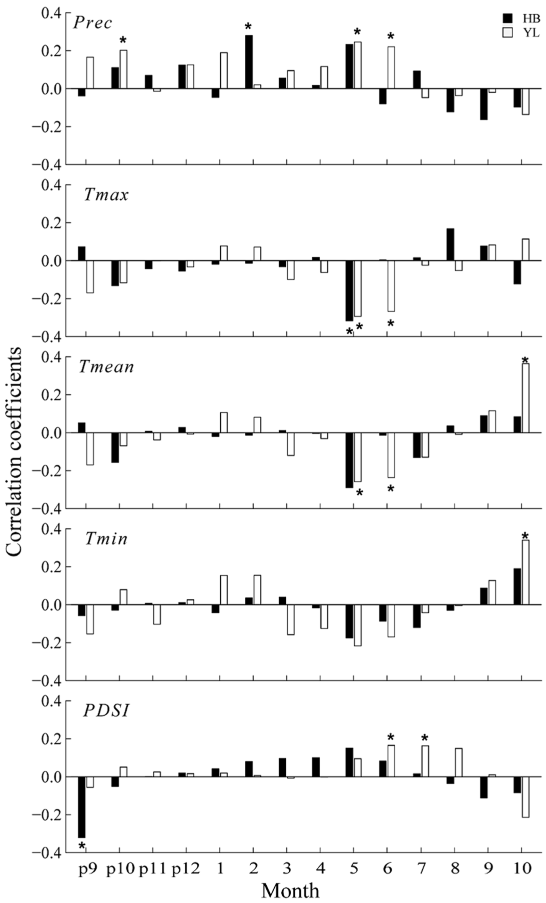

FIGURE 5
Correlation coefficients between residual chronologies and climate variables during the periods between 1966 and 2016. * indicates a significant correlation at $p < 0.05$. p: previous year, the same below.

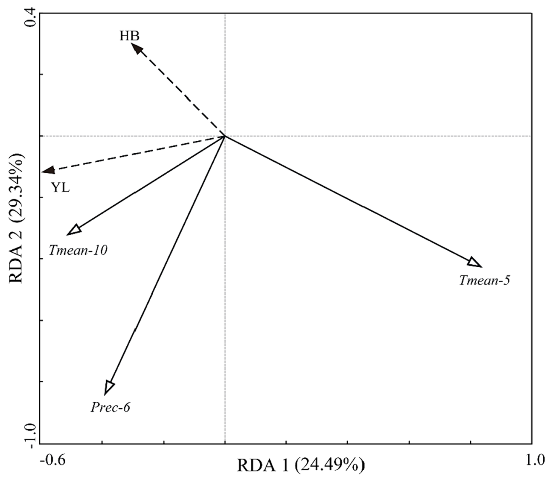

FIGURE 6
The redundancy analysis (RDA) between chronologies and the climate variables (1966–2016). Only significant ($p < 0.05$) climate variables were presented. Tmean-10, mean temperature in current October; Tmean-5, mean temperature in current May; Prec-6, precipitation in current June.

to climate change and reached a significant level from 2012 to 2016 (Figures 7B,D,F).

4 Discussion

4.1 Common response to climate

Both response function analysis and RDA revealed that high temperature (T_{max}) in May restricted the radial growth of *P. yunnanensis* at two sites (Figures 5, 6). In general, temperatures rose rapidly during the early growing season (April to May), but the region does not experience a rapid increase in precipitation during these months (Figure 2). This may cause drought stress for tree growth induced by the acceleration of plant transpiration and soil moisture evaporation, which lead to insufficient water supply (Denmead and Shaw, 1962). Similar results have been reported in other conifers in CHM, such as the *A. georgei* in HB (Sun et al., 2021), *A. forrestii* and *P. likiangensis* in YL (Yang et al., 2022), and *T. dumosa* in YL (Guo G. et al., 2009), indicating the importance of sufficient moisture condition of this period on tree growth in the area. This water-demand effect was also supported by the results of response function analysis, by showing positive relation to May precipitation (Figure 5). High precipitation could compensate for the loss of soil water caused by rapid increase in temperature with high evaporation, consequently alleviate the plant transpiration and avoid stomatal closure. Moreover, the increase in precipitation could supply soil moisture for xylem cell production and the onset of xylogenesis (Shen et al., 2020) during the cambium active period of tree growth in the early growing season (Rossi et al., 2016).

Current October T_{mean} positively affected the radial growth of *P. yunnanensis* (Figure 6), suggesting the importance of the impact of post-growing season temperature on tree growth. During the post-growing season, cambial activity tended to be weakened (Gričar et al., 2007). However, elevated temperatures could stimulate photosynthesis and generate nutrients for tree growth, and prolong the growing season, consequently leading to the formation of wider annual ring widths (Dawadi et al., 2013). Similar results have also been found in the growth of *A. georgei* (Sun et al., 2021) in HB and *Abies fargesii* (Kharal et al., 2017) in adjacent Manan River Valley of central Himalayas.

The common climate variables with inverse effects between two sites were also observed. Excessive precipitation in June had negative impacts on *P. yunnanensis* growth in HB. Tree began to fast growth in June on HB and would benefit from high temperature for photosynthesis (Zhang et al., 2020). However, greater precipitation is generally combined with enhanced cloudiness, reduced solar radiation input, and lower temperatures, which might decrease the photosynthetic process (Fan et al., 2019). The constraints of early summer precipitation on tree growth have also been reported in previous studies in four conifers (Zhang et al., 2020), *P. yunnanensis* (Shen et al., 2020), and *A. georgei* (Yin et al., 2018) in CHM. In comparison with HB, the sampling site is about 300 m lower in YL, water availability was more important than temperature at lower elevation sites (Fan et al., 2009). Xylem cell production benefits from energy and soil moisture during the cambium active phase (Liang et al., 2014) and enough precipitation can satisfy the water demand of the tree growth in the growing season. This was also demonstrated by growth reaction to PDSI in YL, presenting significant and positive correlations with PDSI in current June (Figure 5).

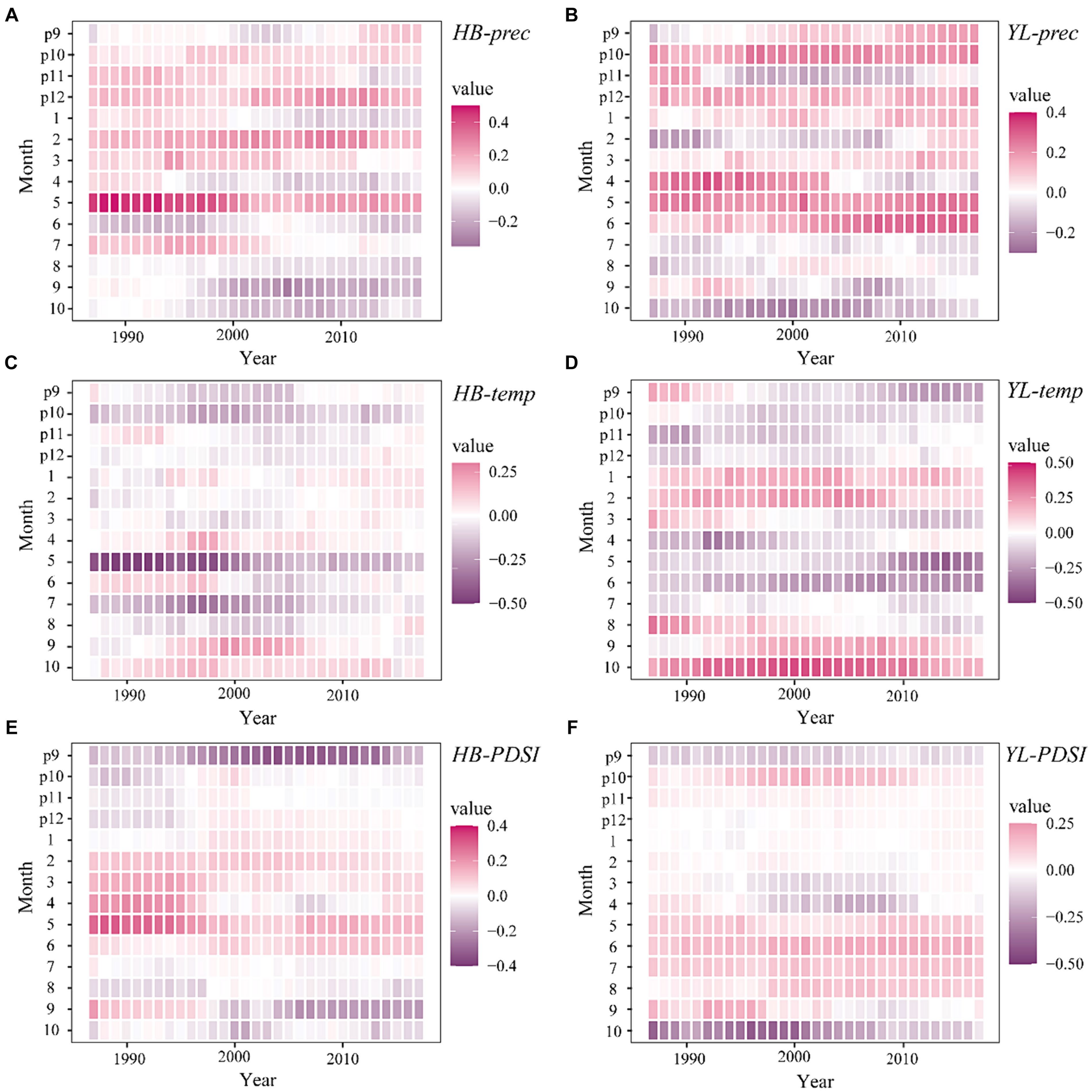

FIGURE 7
Moving interval analysis between chronologies and the monthly total precipitation (prec) **(A)**, monthly mean temperature (temp) **(C)** and Palmer Drought Severity Index (PDSI) **(E)** in HB, and (prec) **(B)**, (temp) **(D)**, (PDSI) **(F)** in YL from previous September to current October (1987–2017). p: previous year.

Furthermore, the observed inverse response can be attributed to variations in soil conditions. The soil is relatively infertile with low organic matter due to steep slopes and shallow soil layers in HB (Su and Wang, 2020), elevated precipitation may trigger soil erosion and therefore endanger its growth. While in YL, the soil is comprised of loam and clay with a higher organic matter content, abundant precipitation may create moist soil conditions for tree growth (Guo L. N. et al., 2009).

4.2 Site-specific climate response

The radial growth of *P. yunnanensis* was affected by winter precipitation in HB (Figure 5). The rise in February precipitation facilitated the formation of a thicker snow cover, effectively shielding roots from potential damage induced by low temperatures and harsh winds at higher altitudes (Zhang et al., 2020). As the snow melted, the heightened soil moisture further supported roots in optimizing water and nutrient uptake, ultimately promoting tree growth (Su and Wang, 2020). The positive effects of winter temperature on tree growth were also highlighted by previous studies at high elevations in the area (Fan et al., 2009; Zhang et al., 2018).

Favorable soil moisture conditions in July promoted the radial growth of *P. yunnanensis* in YL, since adequate soil moisture could accelerate nutrient dissolution and transport, as well as facilitate root absorption, enriching trees with essential nutrients and alleviating drought stress. A similar response pattern to soil moisture was observed by Sun et al. (2020) in Hengduan Mountains, where *P. yunnanensis* tree rings were positively correlated with summer moisture availability.

4.3 The stability dynamics

In general, the results of moving interval analysis approved the findings obtained through response function and RDA, by showing significant correlations in many years for those months (e.g., May, June, July, and October), which presented significant relations to tree growth. Furthermore, the stability of climate-growth relationships exhibited variability on an interannual scale. For example, the strongest correlation between tree growth and May temperature in HB was detected from 1990 to 2000, then the strength of the relationship became weakened after the 21st century. This may be attributed to the noticeable temperature surge in Lijiang during that 10-year period (Figure 3), correspondingly, there was a notable strengthening of the positive correlation between growth and May precipitation during this period. The increased precipitation seemed to alleviate the drought stress caused by the sharp temperature rise. Similar results were also presented by the relationship between tree growth and June precipitation, temperature, and PDSI in YL, and other studies that showed the stability of climate-growth relationships varied with warming periods and abrupt climatic changes in the region (Shen et al., 2020).

4.4 Future tree and forest growth

According to the future climate simulation under the Special Report on Emissions Scenarios (SRES) B2 scenario, the mean temperature in spring, summer, autumn, and winter in Southwest China is projected to increase by 2.6°C, 3.1°C, 2.7°C, and 3.1°C, and precipitation will relatively increase by 8, 7, 6, and 8% in 2071–2,100 (Xu et al., 2005). Incorporating the climate response of tree growth and the prediction of future climate conditions, the productivity of *P. yunnanensis* forests would likely be enhanced. The radial growth of *P. yunnanensis* will benefit from increases in precipitation since precipitation is all positively correlated with tree growth (except June precipitation in HB). Although higher temperature in spring and early summer will inhibit tree growth, increases in precipitation of the corresponding seasons is likely to offset the negative impact. Therefore, the growth of *P. yunnanensis* forests was expected to enhance under future climate change in the area.

5 Conclusion

We studied the climate-growth relationships of *P. yunnanensis* in CHM and predicted the growth of its predominant forest. Both temperature and precipitation affected its growth, and tree growth showed common and site-specific responses to climate change. Moisture conditions in May would be the most critical factor influencing its growth, while June precipitation and current October temperature were other two common factors affecting *P. yunnanensis* growth. Although intense warming of spring and early summer months in the future may exacerbate drought stress on forests, we believe that a high percentage of increased precipitation would offset insufficient water supply induced by warming. According to the results, the radial growth of *P. yunnanensis* may increase under future climate conditions in our study area. Further studies on species' drought response mechanism are required and sustainable strategies of forest management should be focused on improving resistance to drought.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

SX: Validation, Writing – review & editing, Writing – original draft, Visualization, Software, Conceptualization. TY: Writing – review & editing, Methodology, Investigation, Data curation. XS: Writing – review & editing, Methodology, Data curation. HC: Writing – review & editing, Methodology, Data curation. MS: Writing – review & editing, Methodology, Investigation, Data curation. YZ: Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization.

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Conflict of interest

XS was employed by Anji Yinjiang Agriculture Development Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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