Postprint: Separate Effects of Earlywood and Latewood Radial Growth of Larix principis-rupprechtii in Response to Climate Change in Luya Mountain

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Abstract

Tree-ring residual chronologies were established using Larix principis-rupprechtii tree-ring cores collected from three altitudinal gradients in Luya Mountain. Employing dendroclimatological methods and using 1984/1985 as the boundary, correlation analyses were conducted between whole-ring, earlywood, and latewood residual chronologies and climatic elements to investigate the heterogeneous characteristics of radial growth responses to climatic factors at different altitudes for L. principis-rupprechtii during the two periods of 1957-1984 and 1985-2020. The results demonstrated: (1) The radial growth variations of earlywood and latewood at the three altitudes in Luya Mountain during 1957-2020 were difficult to reconcile with the climate warming trend in the study area, exhibiting a divergence in response to temperature factors. (2) During 1957-1984, earlywood growth at low altitude did not exhibit significant correlations with climatic factors, while growing-season precipitation factors (June precipitation) exerted a significant limiting effect on earlywood growth at middle and high altitudes; during 1985-2020, the influence of growing-season precipitation factors (April precipitation) on earlywood growth at low altitude intensified, whereas earlywood growth at middle and high altitudes was primarily significantly positively correlated with January precipitation, indicating that the limiting effect of growing-season climatic factors on earlywood growth at middle and high altitudes weakened. (3) Pre-growing-season nutrient accumulation was crucial for latewood growth of L. principis-rupprechtii in the study area: during 1957-1984, latewood width chronologies at both low and middle-high altitudes showed significant positive correlations with May precipitation; during 1985-2020, radial growth of latewood exhibited significant correlations with pre-growing-season climatic factors (previous November, current January, March, May). (4) Within the two distinct periods, the altered earlywood growth pattern at low altitude

may be caused by drought stress induced by rising temperatures; whereas the difference in earlywood growth patterns at middle and high altitudes may be attributed to temperature increases alleviating the inhibitory effect of low temperatures on earlywood growth in middle and high altitude regions. In summary, with global climate warming, the response characteristics and patterns of earlywood and latewood growth of L. principis-rupprechtii at three altitudes in Luya Mountain to climatic elements differed between the two periods, exhibiting a certain “divergence”phenomenon in response to climatic factors. Future regional climate reconstruction work should consider this divergence phenomenon in tree growth in the region to ensure the reliability of reconstruction efforts.

Full Text

Response Divergence of Radial Growth to Climate Change in Earlywood and Latewood of *Larix principis-rupprechtii* in Luya Mountain

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Abstract

Using tree-ring cores of *Larix principis-rupprechtii* collected from three altitudes on Luya Mountain, we established residual chronologies for whole-ring, earlywood, and latewood width. Employing dendroclimatological methods and using 1984/1985 as a 分界点, we correlated these chronologies with climate variables to investigate heterogeneous response characteristics across two distinct periods (1957-1984 and 1985-2020). Our results reveal four key findings: (1) Radial growth variations in both earlywood and latewood at all three altitudes showed poor alignment with the regional warming trend from 1957 to 2020, indicating a divergence in temperature responses. (2) During 1957-1984, low-altitude earlywood growth exhibited no significant correlation with climate factors, whereas growing-season precipitation (particularly March precipitation) significantly constrained earlywood growth at medium and high altitudes. (3) In the 1985-2020 warming period, growing-season precipitation enhanced its influence on low-altitude earlywood growth, while medium- and high-altitude earlywood growth became primarily associated with January precipitation, suggesting weakened climatic limitation on development. (4) Pre-growth nutrient accumulation proved critical for latewood formation: from 1957-1984, latewood width chronologies at all altitudes showed significant positive correlations with May precipitation; from 1985-2020, latewood radial growth was limited by combined temperature and precipitation factors from the previous November and current-year January, March, and May. These findings demonstrate that under global warming, *L. principis-rupprechtii* at different altitudes exhibits divergent response patterns to climate factors across the two periods, with earlywood and latewood showing distinct "response divergence" phenomena. Future regional climate reconstructions must account for this divergence to ensure reliability.

Keywords: Luya Mountain; *Larix principis-rupprechtii*; elevation gradient; earlywood ring width; latewood ring width; climate change; response divergence

Introduction

Climate change profoundly impacts forest ecosystem structure and function [1]. Trees in high-latitude and high-altitude regions are particularly sensitive to climatic variations [2]. The "divergence problem" in tree growth refers to the phenomenon where trees in high-latitude regions of the Northern Hemisphere, previously limited by temperature, exhibit declining temperature sensitivity under global warming, making their growth trends difficult to reconcile with regional warming patterns [3-5]. Jacoby and D' Arrigo first identified this divergence phenomenon [6], and subsequent research has yielded extensive findings on tree-climate decoupling. For instance, studies in Alaska' s Lake Clark National Park revealed post-1950 growth-climate divergence [7], while Guo et al. [8] documented similar patterns in Markang, Sichuan, following a temperature regime shift.

This divergence phenomenon challenges the uniformitarian principle underlying tree growth-climate relationships and has critical implications for the reliability of climate reconstructions [9]. Moreover, understanding forest ecosystem responses to climate change is essential for assessing their role in global carbon cycling. While most divergence research has focused on high-latitude regions of the Northern Hemisphere [10], studies in mid- and low-latitude areas remain limited [11]. Investigating this phenomenon across broader geographic regions, particularly mid-latitude zones, is necessary to elucidate its spatiotemporal patterns.

Separating earlywood and latewood can extract stronger or differential climate signals [12-14]. Tree-ring studies focusing on earlywood/latewood differentiation have primarily examined ring width and stable isotopes [15-17]. Zhao et al. [18] demonstrated that adjusted latewood width chronologies strongly correlate with July climate factors, enabling reconstruction of Southern China' s summer precipitation since 1888. Luya Mountain, located in North China' s Shanxi Province within the mid-latitude zone, has experienced warming since the 1980s [19]. Previous research showed that warming intensified climate impacts on low-altitude *Picea meyeri* while diminishing effects on high-altitude populations [20]. Although whole-ring responses to warming have been studied [21], earlywood and latewood responses remain poorly understood. This study addresses whether earlywood/latewood growth-climate responses have diverged and how climate change differentially impacts these components. Using independent sample t-tests to analyze interannual climate trends and employing 1984/1985 as a 分界点, we examine divergence phenomena and climate impacts on earlywood/latewood growth, providing valuable insights for forest dynamics and management in North China under global warming.

1.1 Study Area

Luya Mountain (111°50 -112°05 E, 38°35 -38°45 N), the main peak of the Guancen Mountains, represents a major peak in northern Shanxi Province. Located at the source of the Huihe and Fenhe Rivers at the junction of Ningwu, Kelan, and Wuzhai counties, its highest point (Heyeping) reaches 2783 m. The northeast-southwest oriented range forms a natural barrier for East Asian monsoon penetration, creating a pronounced precipitation gradient. Situated in a warm temperate semi-humid zone influenced by Mongolian Plateau climate, the region exhibits continental characteristics with cool, rainy summers and cold, dry winters. Meteorological disasters include frost damage and severe spring droughts in some areas [22].

Vegetation and soils show clear vertical zonation: forest-steppe (1300–1500 m), deciduous broadleaf forest (1500–1700 m), mixed coniferous-broadleaf forest (1350–1700 m), cold-temperate coniferous forest (1700–1850 m), and subalpine shrub-meadow (2450–2772 m). *Larix principis-rupprechtii* primarily occurs in the cold-temperate coniferous forest zone. Soils transition from mountain cinnamon soil to leached cinnamon soil, brown forest soil, and subalpine meadow soil with increasing elevation [23]. The distribution of meteorological stations and sampling sites is shown in [Figure 1: see original paper].

1.2 Climate Data

Meteorological data were obtained from the China Meteorological Data Network (http://data.cma.cn). We selected records from the nearest Wuzhai meteorological station (111°49 E, 38°55 N, 1401.0 m), which has continuous observations since 1957. The study area has a mean annual temperature of 5.3°C (ranging from -12.4°C in January to 20.1°C in July) and mean annual precipitation of 470.7 mm, with 113.8 mm falling in July (the wettest month). This represents a typical rain-heat 同期 pattern [Figure 2: see original paper]. Climate variables included monthly mean temperature and precipitation.

1.3 Sample Collection

Sample collection and processing followed International Tree-Ring Data Bank (ITRDB) standards [24]. We established three sampling sites on Heyeping, the main peak of Luya Mountain . Field investigations revealed that trees at the lower distribution limit (2050 m) were too young, exhibiting pronounced juvenile effects. Therefore, we used the 2303 m site as our low-altitude sample point. Additional sites were located at medium (2393 m) and high (2473 m) elevations, with the high-altitude site representing the natural treeline.

At each site, we collected two cores per tree (at breast height and base) from 20–24 healthy, undisturbed *L. principis-rupprechtii* individuals using 5.15 mm increment borers, yielding 40–48 cores per site. Samples were stored in paper straws for laboratory analysis.

1.4 Chronology Development

In the laboratory, samples were air-dried, polished, and cross-dated. We measured whole-ring, earlywood, and latewood widths to 0.01 mm precision using a LINTAB measuring system. Earlywood-latewood boundaries were identified based on abrupt transitions [25]; for cores with gradual transitions, the midpoint was designated as the boundary under microscopic examination [26].

Cross-dating quality was verified using COFECHA [27]. We selected 40–48 cores with high interseries correlation from each site for analysis. Using ARSTAN [28], we detrended series with negative exponential functions to remove age-related growth trends. Given minimal differences between medium and high altitudes and evidence of similar growth patterns [21], we developed six residual chronologies: low-altitude whole-ring, earlywood, and latewood; and medium-high altitude whole-ring, earlywood, and latewood.

We calculated statistical metrics including mean sensitivity (MS), interseries correlation (R), first principal component variance explained (PCA1%), signal-to-noise ratio (SNR), and expressed population signal (EPS) . All chronologies exceeded the 0.85 EPS threshold, indicating reliable climate signals [29]. Medium-high altitude chronologies showed higher SNR and EPS values than low-altitude chronologies, suggesting greater climate information content.

1.5 Analytical Methods

We used independent sample t-tests to analyze interannual trends in mean temperature and precipitation. Results revealed significant differences in temperature ($P < 0.05$) but not precipitation ($P > 0.05$) between periods, with accelerated warming post-1985 [Figure 4: see original paper]. Based on this, we divided the study period into a cooling phase (1957–1984) and warming phase (1985–2020).

Pearson correlation analysis was performed between tree-ring chronologies and monthly climate variables from the previous June to current September, accounting for lagged growth responses [30]. Moving correlation analysis examined dynamic relationships using 31-year windows [31], calculated in DendroClim2002 [32]. Divergence was assessed by comparing fluctuation characteristics and differential trends between tree-ring indices and climate factors across periods, following methods from previous studies on response divergence in fir species [8, 33].

Results

2.1 Climate Change Characteristics

The lowest mean annual temperature was 3.9°C and lowest annual precipitation was 276.1 mm. Independent sample t-tests comparing 1957-1984 versus 1985-2020 revealed significant temperature differences ($P < 0.05$) but no significant precipitation differences ($P > 0.05$), indicating a warming trend with accelerated temperature increase after 1985 [Figure 4: see original paper]. This aligns with regional warming documented by Zhang et al. [19]. Annual precipitation showed no 分段变化趋势.

2.2 Basic Statistical Characteristics of Earlywood/Latewood Chronologies

Mean sensitivity ranged 0.175-0.230, interseries correlation 0.196-0.251, and first principal component explained variance 53.7%-88.9% , demonstrating sensitivity to climate variability. Sample representativeness (0.958-0.989) and SNR (0.509-0.896) exceeded minimum thresholds, confirming reliable climate signals. Medium-high altitude chronologies exhibited higher SNR and EPS than low-altitude chronologies, indicating greater climate information content.

2.3 Comparison of Fluctuation Characteristics

Boxplots revealed that whole-ring and earlywood indices were slightly higher in 1985-2020 than 1957-1984, while latewood indices were slightly lower in the latter period [Figure 5: see original paper]. No significant differences occurred between periods for whole-ring or earlywood indices at any altitude ($F > 0.05$), though 波动幅度 increased post-1985. Latewood indices showed greater fluctuation in 1957-1984.

Climate variables showed significantly higher temperatures in 1985-2020 ($P < 0.01$) but no precipitation differences [Figure 6: see original paper]. The divergence between tree-ring indices and mean annual temperature widened throughout the study period, particularly after 1985, with temperature values exceeding ring-index values [Figure 7: see original paper]. In contrast, tree-ring indices aligned well with precipitation throughout the study period.

2.4 Correlation Relationships Between Tree Rings and Climate

During 1957-1984, no significant correlations existed between tree-ring width chronologies and monthly mean temperatures. Low-altitude latewood growth was promoted by March precipitation, while medium- and high-altitude earlywood growth showed significant negative correlations with June precipitation [Figure 8: see original paper]. Latewood width chronologies at all altitudes correlated positively with May precipitation.

During 1985-2020, low-altitude earlywood growth correlated significantly with

April precipitation, while medium- and high-altitude earlywood growth correlated with January precipitation [Figure 9: see original paper]. Low-altitude latewood growth was inhibited by previous November temperature, while medium- and high-altitude latewood growth showed significant positive correlations with January temperature and March precipitation. Winter precipitation (previous November) significantly influenced growth at all altitudes in the latter period.

2.5 Dynamic Relationships with Key Climate Factors

2.5.1 Earlywood Growth Dynamics Moving correlation analysis revealed no significant relationships between earlywood width and monthly temperatures throughout the study period [Figure 10: see original paper]. Correlations with June precipitation fluctuated substantially, showing initial increases, subsequent declines, and renewed increases post-1985. Low-altitude earlywood correlations with June precipitation became significantly positive after 1985. Medium- and high-altitude earlywood showed significantly negative correlations with June precipitation in the early period, transitioning to non-significant relationships as temperatures rose.

2.5.2 Latewood Growth Dynamics Latewood growth showed weak correlations with growing-season (June–August) climate factors [Figure 11: see original paper]. Correlations with March precipitation increased throughout the study period, becoming significantly positive after 1985. Previous November temperature showed increasingly negative correlations with low-altitude latewood during the warming period. Medium- and high-altitude latewood correlations with January temperature increased, while relationships with March precipitation fluctuated. The comprehensive influence of pre-growth climate factors intensified over time.

Discussion

3.1 Changing Response Relationships Across Altitudes

Our results demonstrate divergent response patterns across altitudes and wood components. During 1957–1984, low-altitude earlywood showed weak climate correlations, while excessive growing-season precipitation at medium-high altitudes reduced temperature and solar radiation, limiting photosynthesis and earlywood growth [34-36]. This precipitation limitation likely represents indirect temperature limitation, consistent with previous whole-ring studies [19, 21].

During 1985–2020, growing-season precipitation enhanced low-altitude earlywood growth by supplementing soil moisture for photosynthesis [37]. Medium- and high-altitude earlywood showed no significant growing-season climate correlations, indicating weakened climatic constraints—a pattern resembling previous divergence findings [8, 38]. Warming reduced temperature sensitivity at high altitudes while low-altitude growth incorporated more precipitation signals. Increased evapotranspiration under warming reduced soil moisture, potentially inducing drought stress at low altitudes [39].

Latewood growth at all altitudes depended heavily on pre-growth nutrient accumulation. March precipitation promoted latewood formation by enhancing stem water content during spring recovery [40]. Previous November temperature negatively impacted low-altitude latewood by increasing water loss and reducing reserves [41]. Enhanced winter precipitation effects suggest lagged responses, with snow cover insulating soils and providing meltwater for spring growth [42].

3.2 Temperature Effects on Earlywood/Latewood Growth

Low-altitude earlywood correlations with June temperature trended negative throughout the study period, becoming significantly negative after 1985, while correlations with June precipitation became significantly positive after 1985—indicative of drought stress [43]. This pattern shift likely results from temperature-induced water limitation.

Medium- and high-altitude earlywood showed declining negative correlations with June precipitation, transitioning from significant inhibition to non-significance as temperatures rose. This suggests warming alleviated low-temperature constraints at higher elevations, promoting growth—a finding consistent with studies on *Larix olgensis* [44] and *Picea meyeri* [20] in the same region.

Latewood growth correlations with March precipitation strengthened throughout the study period, becoming significant after 1985. With May temperatures below 10°C, latewood growth showed limited direct climate response during the growing season. However, pre-growth climate limitations intensified, indicating that latewood development increasingly relies on early-season nutrient accumulation under climate change.

Conclusion

This study examined climate impacts on earlywood and latewood radial growth of low- and medium-high altitude *L. principis-rupprechtii* in Luya Mountain Nature Reserve over the past 64 years. We identified clear divergence between tree-ring indices and climate variables, with differential responses across altitudes and wood components.

Key conclusions include: (1) Significant divergence occurred between tree-ring indices and mean annual temperature, particularly after 1985, with temperature values exceeding ring-index values. (2) Earlywood response patterns shifted between periods: 1957–1984 showed weak low-altitude climate correlations and strong precipitation limitation at medium-high altitudes; 1985–2020 revealed enhanced growing-season precipitation effects at low altitudes and weakened constraints at medium-high altitudes. (3) Latewood growth depended on pre-growth nutrient accumulation, with increasing influence of previous winter and early growing-season precipitation. (4) Low-altitude earlywood pattern changes likely reflect drought stress from warming, while medium-high altitude changes result from alleviated low-temperature limitation.

These findings demonstrate that divergence phenomena must be considered in future climate reconstructions to ensure reliability.

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