Postprint: Radial Growth Response of Picea schrenkiana to Climate Change at Different Elevations in the Tian Shan Mountains

Authors: Shirenna Jiahan, Zhang Tongwen

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Abstract

To investigate the response relationship between radial growth of Schrenk' s spruce (Picea schrenkiana) at different altitudes and climate factors, tree core samples of Schrenk' s spruce were collected from low, middle, and high altitudes in the Kashi River basin forest of Nileke, Yili, Xinjiang, to establish tree-ring width chronologies for different altitudes. Correlation analysis results between the tree-ring chronologies and meteorological data show that the climate factors affecting radial growth at the three sampling sites are mainly mean temperature and relative humidity, with weak response to precipitation. The radial growth of tree rings at high and low altitudes shows the same response to temperature and relative humidity, with positive response to temperature and negative response to relative humidity, while the middle altitude shows the opposite response to high and low altitudes. Since the climate abrupt change in the study area in 1991, the radial growth of Schrenk' s spruce has exhibited "growth divergence" , with tree-ring width indices at high and low altitudes showing significant decline, while those at middle altitude showing significant increase. Before and after the climate shift point, the response relationship of tree radial growth to temperature and relative humidity is unstable; at middle altitude, the positive correlation with temperature from May to September and negative correlation with relative humidity are significantly enhanced, while at low and high altitudes, the relationship with temperature from July to August shifts to significant negative correlation, and the positive correlation with relative humidity from January to February and July to August is significantly strengthened. According to the response pattern of Schrenk' s spruce to climate factors, rapid temperature increase accelerates water evaporation, causing relative humidity to decrease, and the resulting intensified drought has negative impacts on the growth of Schrenk' s spruce in low and high altitude forest areas, while appropriate warming may have a promoting effect on the growth of Schrenk' s spruce in the middle part of the forest.

Full Text

Preamble

Response of Schrenk Spruce (Picea schrenkiana) Radial Growth to Climate Change at Different Altitudes in the Tianshan Mountains

Shirenna Jiahan[1,2,3], ZHANG Tongwen[2,3], YU Shulong[2,3], JIANG Shengxia[2,3], XU Zhonglin[1]

[1]College of Resources and Environment Sciences, Xinjiang University, Urumqi, Xinjiang, China
[2]Institute of Desert Meteorology, China Meteorological Administration, Urumqi, Xinjiang, China
[3]Key Laboratory of Tree-Ring Physicochemical Research, China Meteorological Administration, Urumqi, Xinjiang, China

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Abstract

To investigate the relationship between radial growth of Schrenk spruce (*Picea schrenkiana*) and climatic factors at different altitudes, tree core samples were collected from low-, middle-, and high-altitude forest sites in the Kashi River basin of Nilka County, Xinjiang. Standard tree-ring width chronologies were established for each altitude zone. Correlation analysis between the chronologies and meteorological data revealed that the primary climatic factors influencing radial growth at all three sampling sites were mean temperature and relative humidity, while the response to precipitation was weak. Tree-ring radial growth at high and low altitudes showed identical responses to temperature and relative humidity, exhibiting positive correlations with temperature and negative correlations with relative humidity. In contrast, the middle-altitude site displayed opposite response patterns. Following the abrupt climate shift in 1991, Schrenk spruce radial growth exhibited a "growth divergence" phenomenon: tree-ring width indices at high and low altitudes declined significantly, while those at middle altitude increased significantly. Before and after this climatic breakpoint, the radial growth responses to temperature and relative humidity were unstable. At middle altitude, the positive correlation with May–September temperatures and negative correlation with relative humidity strengthened markedly. At low and high altitudes, the relationship shifted to a significant negative correlation with July–August temperatures and a significant positive correlation with June–August relative humidity. Based on the response patterns of Schrenk spruce to climatic factors, rapid warming accelerates evaporation, causing relative humidity to decline and drought stress to intensify, which negatively impacts Schrenk spruce growth at low and high altitudes. Conversely, moderate warming may promote growth in the middle-altitude forest zone.

Keywords: Tianshan Mountains; *Picea schrenkiana*; tree rings; different altitudes; climate change; divergence phenomenon

1. Introduction

Global warming is an undeniable reality, with the mid-to-high latitudes of the Northern Hemisphere experiencing the most rapid temperature increases [1-2]. Such warming affects tree growth and alters forest ecosystem structure, function, carbon sequestration, and stability [3]. As climate warming intensifies, tree growth responses to climate change have shifted, leading to unstable tree-ring–climate relationships and divergent growth trends—a phenomenon known in dendroclimatology as the "divergence phenomenon" [4-5]. The emergence of this phenomenon challenges the scientific validity of historical climate reconstructions based on tree-ring data, necessitating widespread research to examine the stability of tree growth responses to climate change across different periods.

Altitude serves as a critical ecological factor that redistributes heat and moisture, creating complex growth environments for trees [6]. Consequently, differential responses of tree growth to climate change across altitudinal gradients have garnered increasing attention. D' Arrigo et al. [5] formally introduced the concept of "divergence," referring to the reduced sensitivity of tree-ring width or density to climate warming. Subsequent studies have documented contrasting growth responses. For instance, Wilmking et al. [6] found that white spruce at the alpine treeline in Alaska exhibited temperature thresholds: within the threshold, ring width correlated positively with temperature, but beyond it, the correlation turned negative. In the European Alps, Norway spruce (*Picea abies*) showed enhanced sensitivity to precipitation and reduced sensitivity to temperature during the 20th century [7]. Yu et al. [8] reported that warming and increased precipitation significantly inhibited the growth of Changbai Mountain larch (*Larix olgensis*). Zhang et al. [9] observed that temperature rise promoted radial growth of Mediterranean pine (*Pinus halepensis*) across all elevations in France' s Sainte Baume forest, yet high-altitude Scots pine (*Pinus sylvestris*) growth declined. Similarly, Zhou et al. [10] found that Korean pine (*Pinus koraiensis*) at mid- and high altitudes on Changbai Mountain showed weakening positive correlations with growing-season temperatures, with a tendency to shift toward negative correlations. Zhang et al. [11] noted that low-altitude Schrenk spruce in the Alatau Mountains of Central Asia exhibited enhanced sensitivity to precipitation under recent warming and wetting trends, suggesting that drought stress induced by rising temperatures may be the primary cause of the divergence phenomenon. Zhang et al. [12] further demonstrated that Siberian larch (*Larix sibirica*) in the eastern Tianshan Mountains showed reduced sensitivity to temperature warming, with low-altitude trees exhibiting more pronounced growth declines.

Xinjiang' s Ili region, located in the arid northwest of China and influenced by continental climate and westerly circulation, represents a sensitive zone for global climate change and a vulnerable ecosystem. It is also one of the earliest regions in China to conduct tree-ring research [13-14]. Numerous studies have confirmed that Schrenk spruce at different altitudes in the Tianshan Mountains exhibits varied responses to climatic factors [15-18]. However, research on the stability of these altitude-specific climate responses remains limited. Therefore, this study addresses three key scientific questions: (1) examining tree growth trends in the Kashi River basin of Ili, Xinjiang, against a backdrop of climate change; (2) identifying the primary climatic constraints on radial growth at different altitudes; and (3) analyzing the stability of radial growth responses to climatic factors across altitudinal zones.

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2. Methods

2.1 Study Area

The study area is located in the Kashi River basin of Nilka County, Xinjiang [Figure 1: see original paper], characterized by a typical temperate continental climate with mixed rainfall-snowmelt runoff formation. Mountain vegetation exhibits clear vertical zonation, transitioning from glacial snow and alpine cushion plants at high elevations to alpine grassland, coniferous forest, and montane meadow-steppe at lower elevations. The montane coniferous zone is dominated by Schrenk spruce, primarily distributed on shady slopes at mid-elevations (1500–2800 m) as pure stands, with soils classified as mountainous gray-brown forest soils [19-20]. Schrenk spruce produces distinct, easily identifiable annual rings and demonstrates high sensitivity to climate change, making it an ideal species for dendroclimatic analysis [21].

2.2 Sample Collection and Chronology Development

Following the principles of dendrochronology [22], we established three sampling sites along an altitudinal gradient in the Kashi River basin forest (Table 1). At breast height (1.3 m), two cores were extracted from each tree perpendicular and parallel to the slope direction using increment borers, totaling 120 cores from 60 trees. Samples were processed in the laboratory through drying, mounting, sanding, and visual cross-dating. Ring widths were measured using a LINTAB5 measuring system with 0.01 mm precision. The COFFCHA program verified ring-width data [23], eliminating dating and measurement errors and removing unsuitable cores to ensure accurate determination of each ring’ s formation year. Growth trends were removed using negative exponential functions in the ARSTAN program, and ring curves were standardized using a double-weighted average method [24]. Three types of chronologies were generated: standardized, residual, and autoregressive. The standardized chronology, containing both high- and low-frequency information and reflecting climate variability across multiple scales [25], was selected for analyzing tree-ring–climate relationships.

2.3 Meteorological Data

Meteorological data (1959–2017) were obtained from the Nilka meteorological station (43°48 N, 82°31 E, 1106 m), the nearest station to the sampling sites. Variables included monthly mean temperature, precipitation, and relative humidity. Annual mean temperature increased significantly at 0.552°C/decade, with maximum temperature rising at 0.699°C/decade and minimum temperature at 0.418°C/decade. Precipitation showed a slow increasing trend, remaining relatively stable at 389 mm annually, concentrated in June–August (accounting for 60% of annual precipitation). Relative humidity declined slightly from 1959–2017 but decreased significantly at 2.572%/decade after 1991, indicating an overall warming-drying trend. Mann-Kendall mutation tests identified significant breakpoints in 1997 for mean temperature, 1991 for precipitation, and 1991 for relative humidity [Figure 3: see original paper]. Based on the earliest breakpoint (1991), the meteorological record was divided into two periods (1959–1990 and 1991–2017) for comparative analysis.

2.4 Analytical Methods

Linear regression was used to analyze trends in meteorological and tree-ring data. The Mann-Kendall nonparametric statistical test identified climate data breakpoints. Pearson correlation coefficients between tree-ring chronologies and meteorological data assessed climate-growth relationships. Moving correlation analysis (30-year window) in the Dendroclim program examined dynamic relationships between chronologies and climate variables, with significance tested at $P < 0.05$ and $P < 0.01$ levels.

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3. Results

3.1 Tree-Ring Chronology Characteristics

Mean sensitivity (MS), a key indicator of chronology quality, reflects climatic constraints and information content. MS values for the three chronologies ranged from 0.137–0.188, decreasing with altitude—consistent with other Tianshan studies [26]. Signal-to-noise ratio (SNR), indicating climate information capacity, ranged from 11.242–23.905, with values >10 considered excellent [27]. Expressed population signal (EPS) exceeded the 0.85 threshold for all sites, confirming that the chronologies represent regional Schrenk spruce growth characteristics [28]. First-order autocorrelation coefficients were relatively high (0.747–0.822), indicating strong influence of previous-year climate on radial growth [29].

Inter-chronology correlations over the common period (1880–2017) were significant ($P < 0.05$), but decreased with altitudinal separation (Table 3). Tree-ring width index trends showed increasing growth at all altitudes before 1991, with high-altitude growth increasing most significantly. However, after the 1991 climate breakpoint, high- and low-altitude indices declined significantly while middle-altitude indices increased significantly [Figure 4: see original paper], demonstrating divergent growth trends across altitudes.

3.2 Climate-Growth Relationships Across Altitudes

Considering lag effects, we analyzed correlations between chronologies and climate data from May of the previous year to September of the current year [Figure 5: see original paper]. Before the 1991 breakpoint, climate-growth relationships were relatively stable. Temperature responses differed by altitude: high and low altitudes showed negative correlations with previous-year May–June temperatures (significant at high altitude), while middle altitude exhibited significant positive correlations with previous-year May–June and current-year May temperatures. Precipitation responses were weak and inconsistent: low altitude showed significant positive correlations with previous-year July precipitation; middle altitude with current-year May precipitation; and high altitude with significant negative correlations with previous-year July precipitation. Relative humidity responses opposed temperature responses: high and low altitudes showed significant positive correlations with previous-year May–June and current-year June–August humidity, while middle altitude showed significant negative correlations with most months.

After 1991, these relationships became unstable. High and low altitudes shifted to significant negative correlations with July–August temperatures and strengthened positive correlations with June–August relative humidity. Middle altitude enhanced its positive temperature correlation (May–September) and negative humidity correlation.

3.3 Dynamic Climate-Growth Relationships

Moving correlation analysis revealed enhanced sensitivity to July–August temperatures and June–August relative humidity after 1991 [Figure 6: see original paper]. High and low altitudes transitioned from positive to significant negative correlations with July–August temperatures around 1991, while middle altitude's positive temperature correlation strengthened. Similarly, all sites showed enhanced sensitivity to June–August relative humidity after 1991: high and low altitudes strengthened positive correlations, while middle altitude intensified negative correlations. Precipitation relationships also became unstable, with high and low altitudes strengthening negative correlations with July precipitation after 1991, while middle-low altitudes weakened negative correlations with May precipitation.

4. Discussion

4.1 Altitudinal Variation in Climate-Growth Responses

Our findings reveal distinct altitudinal patterns in Schrenk spruce climate responses. At high and low altitudes, radial growth is primarily moisture-limited, showing negative correlations with temperature and positive correlations with relative humidity. This reflects the species' preference for humid conditions and sensitivity to soil moisture availability. Physiologically, high temperatures during the previous growing season (May–June) enhance transpiration, depleting stored water reserves and reducing subsequent year' s growth [30]. At high altitudes, intense solar radiation and elevated July–August temperatures exacerbate soil evaporation and vegetation transpiration, creating water deficits that inhibit growth [31-32]. This aligns with studies on treeline Schrenk spruce on the northern Tianshan slopes [33].

In contrast, middle-altitude growth is primarily temperature-limited, showing significant positive correlations with May–September temperatures. Calculated mean May–September temperature at this site is approximately 13.6°C, near the lower threshold for optimal Schrenk spruce growth [34]. Under moisture-sufficient conditions near the maximum precipitation belt (1900–2200 m) on the northern Tianshan slopes [35], moderate warming enhances photosynthesis and promotes growth. This pattern resembles findings for Siberian larch in the eastern Tianshan Mountains [36].

The weak precipitation response reflects complex hydrothermal conditions in the Ili region. While low and middle altitudes show positive precipitation responses and high altitude shows negative responses, relative humidity emerges as a more direct moisture indicator. The inverse relationship between temperature and relative humidity responses confirms that moisture availability, rather than precipitation per se, constrains growth at high and low altitudes.

4.2 Divergent Growth Responses to Climate Change

The 1991 climate breakpoint triggered divergent growth trajectories: high- and low-altitude chronologies declined significantly while middle-altitude chronologies increased. This "growth divergence" reflects altered hydrothermal regimes under climate warming [37-38]. The intensified positive correlation between high/low-altitude growth and June–August relative humidity after 1991 indicates that warming-induced drought stress increasingly limits growth at these elevations. July–August temperatures exceeding optimal thresholds accelerate evapotranspiration, reducing water availability during the critical earlywood growth period [39-40].

Conversely, middle-altitude trees benefit from enhanced May–September temperature sensitivity under adequate moisture conditions. The warming trend, coupled with increasing precipitation, creates favorable conditions for photosynthesis and carbon accumulation, promoting radial growth [41-42]. This divergence pattern—where moisture-limited sites decline and temperature-limited sites benefit—has been documented across multiple mountain systems [43-44].

Our results underscore that rapid warming intensifies evaporation, reduces relative humidity, and exacerbates drought stress, negatively impacting Schrenk spruce at low and high altitudes. Moderate warming, however, may enhance growth in the middle-altitude forest zone where moisture is less limiting.

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5. Conclusions

1. All altitudinal chronologies contain substantial environmental information and reliably represent regional Schrenk spruce radial growth characteristics (EPS > 0.85).
2. Following the 1991 climate breakpoint, high- and low-altitude tree-ring widths declined while middle-altitude widths increased, demonstrating a clear "growth divergence" phenomenon across altitudes.
3. Climate-growth response patterns differ by altitude: high- and low-altitude radial growth is primarily moisture-limited, while middle-altitude growth is temperature-limited.
4. The climate breakpoint destabilized temperature and relative humidity relationships. High and low altitudes developed significant negative correlations with July–August temperatures and strengthened positive correlations with June–August relative humidity. Middle altitude enhanced positive temperature correlations and negative humidity correlations.
5. Under climate warming, intensified evaporation and drought stress may negatively impact Schrenk spruce growth at low and high altitudes, while moderate warming may benefit middle-altitude forests. These findings highlight the need to assess response stability in dendroclimatic reconstructions and monitor climate impacts on forest ecosystem dynamics in the western Tianshan Mountains.

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Note: Figure translations are in progress. See original paper for figures.