

Response of *Picea schrenkiana* Radial Growth to Climate Change on the Central Northern Slope of the Tianshan Mountains (Postprint)

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Abstract

Analyzing tree radial growth responses to climate change facilitates accurate prediction of future forest dynamics. The mid-montane zone of the northern slopes of the Tianshan Mountains hosts extensive temperate coniferous forests dominated by Schrenk's spruce (*Picea schrenkiana*) as a single species. This study collected high-altitude Schrenk's spruce tree core samples from this region and employed dendrochronological methods to investigate the response characteristics of Schrenk's spruce radial growth to climatic factors and drought events. The results indicated: (1) During 1960–2020, the tree-ring width index of Schrenk's spruce displayed an extremely significant increasing trend, with no growth decline observed, indicating favorable growth conditions for Schrenk's spruce in recent periods. (2) The tree-ring width of Schrenk's spruce was significantly positively correlated with June–August temperatures, April precipitation, and monthly scPDSI values except for July of the current year. Moving correlation analysis demonstrated that the relationship between Schrenk's spruce tree-ring width and climatic factors was unstable; after 1991, the positive response of spruce to climatic factors was further enhanced. (3) The percentage change in radial growth of Schrenk's spruce fell below –25% during 1879–1880, indicating that growth decline occurred from 1879–1885. With increasing frequency and intensity of drought events, the resistance and recovery capacity of Schrenk's spruce to drought events decreased. When spruce experienced sudden drought events after prolonged exposure to relatively water-sufficient environments, its resistance declined severely, predisposing it to growth decline. In summary, under the background of climate change, recent warming has remained beneficial for radial growth of high-altitude Schrenk's spruce in this region. However, the concomitant increase in drought frequency and intensity during the warming process will further reduce the resistance and recovery capacity of Schrenk's spruce, elevating the risk of growth decline. In the near term, Schrenk's spruce

will continuously experience a trade-off between growth promotion by warming and growth inhibition by drought; the ultimate outcome requires further observation and research. Multiple approaches should be employed to closely monitor its growth dynamics in the future.

Full Text

Radial Growth Response of *Picea schrenkiana* to Climate Change in the Middle Section of the Northern Slope of the Tianshan Mountains

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Abstract

Analyzing tree radial growth responses to climate change is essential for accurately predicting future forest dynamics. The temperate coniferous forest dominated by Schrenk's spruce (*Picea schrenkiana*) is widely distributed across the mid-mountain zone on the northern slope of the Tianshan Mountains. This study collected tree-ring core samples from high-altitude *P. schrenkiana* stands and employed dendrochronological methods to investigate the response characteristics of spruce radial growth to climatic factors and drought events. The results showed that: (1) From 1960 to 2020, the tree-ring width index of *P. schrenkiana* exhibited a highly significant upward trend without any growth decline, indicating favorable growth conditions in recent years. (2) Tree-ring width was primarily positively correlated with temperature from June to August, precipitation in April, and scPDSI in all months except July. Moving correlation analysis revealed an unstable relationship between tree-ring width and climatic factors. After 1991, the positive response of spruce to climatic factors was further strengthened. (3) The percentage of radial growth change in *P. schrenkiana* was less than -25% during 1879–1880, indicating a growth decline from 1879 to 1885. With increasing drought frequency and intensity, the resistance and recovery of *P. schrenkiana* to drought events decreased. When spruce experienced prolonged periods in relatively water-sufficient environments

followed by sudden drought events, its resistance declined severely, making it prone to growth decline. In summary, under climate change scenarios, warming is still expected to promote radial growth of high-altitude *P. schrenkiana* in this region in the near future. However, the accompanying increase in drought frequency and intensity during the warming process will further reduce spruce resistance and recovery, elevating the risk of growth decline. In the near term, *P. schrenkiana* will continuously struggle between growth promotion by warming and growth inhibition by drought. The ultimate outcome requires further observation and research, and multiple approaches should be implemented to closely monitor its growth dynamics.

Keywords: *Picea schrenkiana*; tree ring; radial growth; climate change; resistance; recovery; northern slope of the Tianshan Mountains

1 Introduction

Global climate change has caused temperature increases and altered precipitation patterns in many regions, leading to increased frequency and intensity of droughts—a trend projected to continue in the future. Since the mid-1980s, Xinjiang has experienced warming and increased precipitation at the regional scale, exhibiting a “warm-humidification” trend. However, after 2008, the entire region has become drier, with Xinjiang’s climate showing a shift from “warm-humidification” to “warm-dryification.”

Climate change affects tree growth by altering temperature and water availability, creating specific physiological stresses. In arid and semi-arid regions, drought can cause tree growth decline and even mortality, triggering forest degradation. In the Helan Mountains, drought has caused growth decline in Chinese pine (*Pinus tabulaeformis*) and Qinghai spruce (*Picea crassifolia*), with potential for future intensification. In Northeast China, drought has induced growth decline in Chinese pine, with local contraction and overall northward shift of its distribution boundary, leading to high mortality rates in aspen (*Populus davidiana*) and altered forest structure. This inhibitory effect is particularly pronounced in environmentally harsh arid and semi-arid regions.

Tree rings faithfully record extreme climatic events such as drought experienced during tree radial growth, serving as one of the most objective, sensitive, and easily identifiable indicators for measuring tree growth dynamics. A tree’s ability to cope with drought depends primarily on its capacity to resist during drought events and recover quickly afterward. Lloret et al. proposed ecological resilience indicators based on tree rings: Resistance (Rt) and Recovery (Rc). Trees with weak resistance are prone to growth decline after extreme drought, while the percentage of radial growth change (GC) can determine whether growth decline has occurred. These tree-ring data can quantify the degree, duration, and spatial extent of climate change impacts, particularly drought.

The Tianshan Mountains represent an ecologically sensitive region where climate variability is amplified, effectively reflecting regional responses to global climate

change. Research suggests that the Tianshan region may enter a multi-decadal period of below-average precipitation in the future. Schrenk's spruce is widely distributed across the 1760–2760 m mid-mountain zone on shady and semi-shady slopes, accounting for 90% of the total forest area in the Tianshan forest region. This species plays a crucial role in regulating local climate and promoting carbon cycling. With clear annual rings, long chronologies, and high sensitivity to climate, Schrenk's spruce is an ideal species for studying tree radial growth-climate relationships.

Previous research on *P. schrenkiana* in the Tianshan region has primarily focused on analyzing differences in tree-climate relationships among various tree species, diameter classes, tree ages, longitudes, aspects, and altitudes. However, studies on high-altitude *P. schrenkiana* responses to climate change, particularly drought, remain limited and are mainly concentrated in the eastern Tianshan. Given the high topographic and climatic heterogeneity in the Tianshan region, with substantial local variations in moisture conditions, targeted research in different areas is necessary. Therefore, this study collected tree-ring samples from high-altitude *P. schrenkiana* stands in the middle section of the northern Tianshan slope to analyze response characteristics of spruce radial growth to climate change. The study aims to address three scientific questions: (1) What are the radial growth characteristics of high-altitude *P. schrenkiana* in the study area under climate change? (2) What are the key climatic factors limiting *P. schrenkiana* radial growth, and is the response relationship stable? (3) How do resistance and recovery of *P. schrenkiana* change under drought events, has growth decline occurred, and what is the relationship between them? This research provides a theoretical basis for predicting the distribution range and development direction of *P. schrenkiana* forests in the region under climate change.

2 Materials and Methods

2.1 Study Area

The study area is located in the Banfanggou Forest Farm within the Urumqi River mountainous watershed on the middle section of the northern Tianshan slope (87°07'–87°28'E, 43°14'–43°26'N). The region has a temperate continental climate. Climate data covering the study area show that from 1960 to 2020, the mean annual temperature was -1.65°C, mean annual maximum temperature was 5.13°C, and mean annual minimum temperature was 8.43°C. July was the warmest month, with mean monthly maximum temperature of 19.4°C, mean monthly temperature of 11.9°C, and mean monthly minimum temperature of 4.5°C. January was the coldest month, with mean monthly maximum temperature of -8.2°C, mean monthly temperature of -14.8°C, and mean monthly minimum temperature of -21.5°C. Mean annual precipitation was 222 mm, with April–September precipitation accounting for 85% of total annual precipitation.

2.2 Sample Collection and Chronology Development

Sampling plots were established at 2600 m altitude in Banfanggou Forest Farm. Healthy *P. schrenkiana* trees with similar site conditions were selected. Two increment cores were collected from each tree at breast height (1.3 m) along parallel and perpendicular slope directions. Samples were stored in paper straws with detailed sampling information. In the laboratory, cores were air-dried, mounted, and sanded following standard dendrochronological procedures. Annual rings were visually dated under a microscope, and ring widths were measured using a LINTAB5 ring analyzer (Rinntech, Heidelberg, Germany). After obtaining raw ring-width data, the COFFCHA program was used for cross-dating, followed by quality control of cross-dating results. Cores with low correlation to the master chronology were removed, retaining 47 cores from 28 trees. The ARSTAN program was used to remove growth trends with a negative exponential function, and a biweight robust mean was applied to create the final standard chronology.

To minimize interference from individual anomalous years, a 5-year moving average was used to calculate the growth change percentage (GC) for *P. schrenkiana*. The formula is:

$$GC_i = \frac{\overline{RW}_{i-5 \text{ to } i-1} - \overline{RW}_{i+1 \text{ to } i+5}}{\overline{RW}_{i-5 \text{ to } i-1}} \times 100\%$$

where GC_i represents the radial growth change percentage in year i , and \overline{RW} represents the mean ring-width index for the 5-year periods before (excluding year i) and after (including year i) the target year. A negative GC_i value indicates suppressed radial growth, and $GC_i < -25\%$ indicates growth decline.

Resistance (Rt) and recovery (Rc) were calculated as follows:

$$Rt = \frac{G_d}{G_{pre}}$$

$$Rc = \frac{G_{post}}{G_d}$$

where G_{pre} represents the mean ring-width index for the 5 years before the drought event, G_d represents the ring-width index in the drought year, and G_{post} represents the mean ring-width index for the 5 years after the drought event. $Rt > 0.75$ indicates strong resistance to drought, while $Rc > 1.25$ indicates high recovery after drought. Note that for the 2020 drought event, only resistance could be calculated as no post-drought data were available.

2.3 Meteorological Data

Given significant elevation differences between sampling sites and nearby meteorological stations, gridded climate data were used. The CRU (Climatic Re-

search Unit) dataset from the University of East Anglia, obtained from the Royal Netherlands Meteorological Institute (<http://climexp.knmi.nl>), provides reliable long-term, high-resolution climate data widely used in dendrochronology. Data extracted for the sampling location (43.00°–43.50°N, 87.00°–87.50°E) at 0.5° × 0.5° resolution included monthly mean maximum temperature, monthly mean temperature, monthly mean minimum temperature, monthly precipitation, and the self-calibrating Palmer Drought Severity Index (scPDSI). The scPDSI is an improved index that considers location-specific soil surface characteristics, providing more accurate and comparable results across different climate conditions. Positive scPDSI values indicate wet conditions, while negative values indicate drought, with more negative values representing more severe drought. According to the scPDSI drought classification, $\text{scPDSI} \leq -1$ indicates light drought, $-2 < \text{scPDSI} \leq -1$ indicates moderate drought, $-3 < \text{scPDSI} \leq -2$ indicates severe drought, and $\text{scPDSI} \leq -3$ indicates extreme drought. Drought years were selected based on $\text{scPDSI} \leq -2$.

2.4 Data Analysis

Pearson correlation analysis was used to examine relationships between tree-ring width and climate factors. Considering the lag effect of previous-year climate on tree growth, climate factors from May of the previous year to September of the current year were included in the analysis. Moving correlation analysis was performed with a 31-year window and 1-year step to observe dynamic changes in relationships between spruce radial growth and climate factors over the past 60 years. The drought frequency was calculated as the ratio of months with $\text{scPDSI} \leq -1$ to total months in a year, while drought intensity was calculated as the ratio of cumulative months with $\text{scPDSI} \leq -1$ to consecutive drought months in a year.

3 Results and Analysis

3.1 Climate Change in the Study Area

From 1960 to 2020, mean annual maximum temperature, mean annual temperature, and mean annual minimum temperature showed highly significant increasing trends ($P < 0.01$), with rates of $0.234^{\circ}\text{C} \cdot (10\text{a})^{-1}$, $0.332^{\circ}\text{C} \cdot (10\text{a})^{-1}$, and $0.429^{\circ}\text{C} \cdot (10\text{a})^{-1}$, respectively. The warming trend was primarily driven by rapid increases in minimum temperature. Precipitation increased significantly at a rate of $10.414 \text{ mm} \cdot (10\text{a})^{-1}$ ($P < 0.05$).

3.2 Statistical Characteristics of the Standard Chronology

To preserve low-frequency climate information, a tree-ring width standard chronology was developed. Key statistical features are presented in . The chronology had relatively low mean sensitivity (0.162) and standard deviation (0.204), indicating limited high-frequency climate information. However, the signal-to-noise ratio (SNR) of 10.414 and first-order autocorrelation (AC1) of

0.714 suggest the chronology contains substantial climate information and that radial growth is strongly influenced by previous-year climate conditions. The expressed population signal (EPS) exceeded the 0.85 threshold required for dendroclimatological analysis, indicating the chronology well represents radial growth characteristics of *P. schrenkiana* in the study area.

3.3 Tree Radial Growth Changes and Decline Processes

The percentage of radial growth change in *P. schrenkiana* was less than -25% during 1879–1880, indicating a growth decline from 1879 to 1885. From 1960 to 2020, no growth decline occurred, and the ring-width index showed a highly significant upward trend ($P < 0.01$), indicating favorable growth conditions.

3.4 Resistance and Recovery of *P. schrenkiana* to Drought Events

P. schrenkiana showed relatively strong resistance but weak recovery to drought events. As drought frequency or intensity increased, spruce exhibited increased resistance but decreased recovery ($P > 0.05$).

3.5 Correlations Between Tree-Ring Width and Climate Factors

At the monthly scale, tree-ring width was significantly positively correlated with mean maximum temperature from June to August, mean temperature in June, precipitation in April, and scPDSI in all months except July. At the seasonal scale, ring width was significantly positively correlated with summer mean maximum temperature, summer mean temperature (both previous and current year), and mean minimum temperature across all seasons. Ring width was also significantly positively correlated with previous summer precipitation and scPDSI across all seasons.

Moving correlation analysis revealed unstable relationships between tree-ring width and climate factors. Since 1991, correlations with temperature in June and July strengthened from non-significant to significant positive relationships. The relationship with April precipitation also strengthened from non-significant to significant positive after 1991. Similarly, correlations with scPDSI in June and July strengthened from non-significant to significant positive since 1991.

4 Discussion

4.1 Key Climate Factors Limiting *P. schrenkiana* Radial Growth

P. schrenkiana radial growth was significantly positively correlated with minimum temperature in most months and with precipitation in April, but significantly correlated with scPDSI in all months except July. The positive correlation with temperature during the current and previous growing seasons reflects that photosynthetic rates depend primarily on temperature. Below threshold temperatures, appropriate warming enhances enzyme activity in leaves, accelerating photosynthesis to accumulate carbohydrates for current and subsequent

year growth. The positive correlation with previous-year temperature is particularly important, as photosynthesis continues even when growth ceases, and higher temperatures facilitate normal metabolism and protect active tissues from cold damage.

April precipitation is crucial as it marks the transition from dormancy to active growth. Adequate precipitation increases soil moisture, promoting cambial cell production, differentiation, and xylem formation, while also helping trees enter the growing season earlier. While radial growth showed positive correlations with temperature, scPDSI, and precipitation, correlations with temperature and scPDSI were stronger than with precipitation alone. The significant positive correlation with scPDSI across most months (85% of months) indicates high sensitivity to drought. scPDSI serves as an excellent proxy for drought severity—lower values indicate less plant-available soil water and more severe drought stress. This demonstrates that soil moisture conditions and low temperature are key limiting factors for high-altitude spruce growth, consistent with findings for Qinghai spruce in the Qilian Mountains and some species in the Rocky Mountains.

4.2 Dynamic Response of *P. schrenkiana* Radial Growth to Climate Factors

Although scPDSI is fundamentally determined by precipitation, in this high-altitude region near the treeline, most precipitation falls as snow that cannot fully melt into soil water for tree uptake. In this context, temperature acts as an “initiator”—snow and ice in the ground require higher temperatures to melt and become available to trees. Consequently, warming increases plant-available soil water. Despite the overall “warm-dryification” trend in Xinjiang, the study area’s high altitude means warming still benefits spruce growth by alleviating low-temperature limitations.

Since 1991, the positive response of spruce to climate factors has strengthened significantly. Correlations with June–July temperature, April precipitation, and June–July scPDSI all intensified from non-significant to significant positive relationships. This enhanced sensitivity reflects that as temperatures rise, photosynthesis and transpiration increase, raising water demand. The warming rate in the study area ($0.332^{\circ}\text{C} \cdot (10\text{a})^{-1}$) exceeds the national average ($0.26^{\circ}\text{C} \cdot (10\text{a})^{-1}$), and this accelerated warming has made spruce growth increasingly dependent on temperature and moisture availability.

4.3 Growth Decline History and Response to Drought Events

The growth decline during 1879–1885 coincided with a dry period identified in regional climate reconstructions. Prior to this decline, a relatively wet period (1796–1865) had created favorable conditions for moisture-loving spruce. However, the subsequent dry period (1879–1885) overlapped with a warm period, creating conditions where drought events were highly probable. During

prolonged wet phases, trees undergo physiological and structural changes such as increased leaf area, reduced root growth, and decreased xylem resistance to embolism, which reduce drought resistance. When such preconditioned trees encounter sudden drought, they are more vulnerable to growth decline.

The 1879–1885 drought event had high frequency (26%) and intensity (-2.60), with long duration that likely caused substantial physiological damage. Analysis of five drought events since 1960 shows that as drought frequency and intensity increase, both resistance and recovery decrease. Notably, during the 1974 drought, despite moderate intensity (-2.19), resistance was the lowest (0.54) among all events. This occurred because the preceding period had relatively wet conditions (scPDSI reached slightly wet levels), and spruce physiological characteristics had adapted to moist environments, making the sudden drought difficult to resist. This pattern demonstrates that trees experiencing long-term water sufficiency lose drought resistance capacity, and when such preconditioned trees face prolonged drought, they are more likely to experience severe growth decline.

5 Conclusion

From 1960 to 2020, climate change characterized by warming promoted radial growth of high-altitude *P. schrenkiana* in the study area. Tree-ring width was significantly positively correlated with June–August temperature, April precipitation, and scPDSI in all months except July. The positive responses to soil moisture availability, growing-season temperature, and April precipitation have strengthened over time. While *P. schrenkiana* depends on warming to release low-temperature limitations, it is also affected by soil water deficits caused by warming. Low temperature and drought stress have become the main factors limiting radial growth in the study area.

High-altitude *P. schrenkiana* exhibits high resistance but weak recovery to drought. With increasing drought frequency and intensity, both resistance and recovery decline. When spruce experiences prolonged periods in water-sufficient environments, its ability to resist drought decreases, making it highly susceptible to severe radial growth reduction and growth decline when drought occurs. Under continued climate warming and increasing drought frequency, high-altitude *P. schrenkiana* in the study area will face more frequent fluctuations between growth promotion by warming and growth inhibition by drought. The ultimate outcome requires further observation. Future research should employ multiple approaches, including wood anatomy analysis, micro-core sampling, and intra-annual/seasonal/daily radial growth monitoring, to clarify the development direction of *P. schrenkiana* forests.

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