Radial Growth Characteristics of Picea schrenkiana at Different Stem Heights and Its Response to Climate in the Yili Mountains (Postprint)

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Abstract

Tree-ring samples were collected at trunk heights of 1.3 m, 5 m, 10 m, 15 m, 20 m, and 25 m from Picea schrenkiana trees in the Ili region of Xinjiang, and tree-ring width chronologies were developed. Correlation analysis was employed to determine the response relationships and stability of radial growth to climatic elements at different trunk heights, and to calculate the relative and absolute contribution rates of various meteorological factors. The results indicate: (1) Different trunk heights exhibit similar characteristics of radial growth variation, with the effects of mean temperature and precipitation primarily manifested as significant negative correlations between tree-ring width at each trunk height and September precipitation of the current year, significant positive correlations with November mean temperature of the previous year, and additionally influenced by July precipitation of the current year at trunk heights from 5 m to 25 m. (2) Quantifying the influence of meteorological factors at each trunk height through contribution rates reveals that mean temperature is the main influencing factor at 1.3 m and 5 m trunk heights, whereas precipitation is the main influencing factor at 10 m, 15 m, 20 m, and 25 m trunk heights. (3) Moving correlation analysis demonstrates that the stability of climate change responses varies among different trunk heights, mainly characterized by weakening correlations with December mean temperature of the previous year at all trunk heights, correlations with June mean temperature of the current year that first strengthen then weaken, and strengthening negative correlations with September mean temperature of the previous year; negative correlations with September precipitation of the current year strengthen at trunk heights from 1.3 m to 15 m, while correlations with January precipitation of the current year weaken at trunk heights from 10 m to 25 m. Analyzing the relationship between radial growth and climatic elements at different trunk heights facilitates understanding of the differences in climate responses of radial growth at various trunk heights and provides a reference for conducting more precise climate

reconstruction.

Full Text

Preamble

Characteristics of Radial Growth at Different Trunk Heights of Picea schrenkiana and Its Climate Response in the Ili Mountainous Region

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Abstract: To analyze the radial growth characteristics of Picea schrenkiana at different trunk heights and their response relationships and stability to climatic elements, we collected tree-ring samples at six trunk heights (1.3 m, 5 m, 10 m, 15 m, 20 m, and 25 m) in the Ili region of Xinjiang and developed tree-ring width chronologies for each height. Through correlation analysis, we determined the response relationships between radial growth at different trunk heights and climatic elements and their stability, and calculated the relative and absolute contribution rates of various meteorological factors. The results indicate: (1) Different trunk heights exhibit similar radial growth variation patterns, and the effects of mean temperature and precipitation are manifested as significant positive correlations between tree-ring width at all trunk heights and September precipitation of the current year, as well as November mean temperature of the previous year. Additionally, the 5–25 m trunk heights show a significant positive correlation with July precipitation of the current year, while the 1.3 m trunk height shows a significant negative correlation with June precipitation of the current year and a significant positive correlation with September mean temperature of the previous year. (2) Through contribution rate analysis to quantify the influence of meteorological factors at each trunk height, temperature is identified as the primary influencing factor at the 1.3 m and 5 m trunk heights, while precipitation becomes the primary factor at 10 m, 15 m, 20 m, and 25 m heights. (3) Moving correlation analysis reveals differences in the stability of climate response among trunk heights, mainly showing that the correlation with December mean temperature of the previous year weakens at all heights; the correlation with June mean temperature of the current year first strengthens then weakens; the negative correlation with September mean temperature of the previous year strengthens; and the negative correlation with September precipitation of the current year strengthens at 1.3 m, 5 m, 10 m, and 15 m heights, while the correlation with January precipitation weakens at 10 m, 15 m,

20 m, and 25 m heights. Analyzing the relationship between radial growth and climatic elements at different trunk heights helps understand the differential climate responses across heights and provides a reference for conducting more precise climate reconstructions.

Keywords: Picea schrenkiana; tree-ring; trunk height; radial growth; climate response

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Tree-ring data are widely applied in global climate change research due to their accurate dating, broad spatial coverage, and ease of collection, playing an important role in analyzing centennial to millennial-scale climate variations. Because collecting tree-core samples at breast height is convenient and generally considered representative of overall tree radial growth, most dendrochronological analyses have traditionally been based on breast-height samples for climate response and reconstruction studies. However, research indicates that factors such as tree condition, natural environment, and physiological characteristics affect different trunk heights, causing variations in radial growth patterns. Furthermore, the response relationships to climatic elements differ across trunk heights. For example, Zhang et al. found that Schrenk' s spruce (Picea schrenkiana) at 1.3 m trunk height shows higher sensitivity to climate elements than other heights. Liu et al. reported that under global warming, radial growth of some trees in high northern latitudes exhibits unstable responses to climate, leading to different growth patterns across spatial regions, altitudinal gradients, and even within the same species.

To address the dynamic response of tree radial growth to climate change under global warming, numerous scholars have conducted related studies on species such as Juniperus seravschanica, Larix sibirica, and Pinus koraiensis across different regions. These studies have examined variations in altitude, slope aspect, and between species, but research on tree-ring parameters at different trunk heights within the same species remains relatively limited. The Tianshan Mountains, located in the arid region of Central Asia with large climate fluctuations and sensitive response to global change, host extensive old-growth coniferous forests including Schrenk' s spruce, making it an ideal region for dendroclimatic research. Previous tree-ring studies in the Tianshan have focused on parameters including width, density, and isotopes, but most have used breast-height samples. Based on this research background and targeting the weak areas of tree-ring research in the Tianshan, our team conducted multi-point sampling of Schrenk' s spruce in the Ili region of Xinjiang to establish more regionally representative tree-ring width chronologies at different trunk heights. This study aims to investigate tree growth-climate responses to deepen understanding of the relationships between radial growth at different trunk heights and meteorological factors and their response stability, attempting to more comprehensively reveal the radial growth patterns of Schrenk' s spruce in the Tianshan region.

1.1 Sample Collection and Processing

The study area is located in the mountainous regions of Tekes and Gongliu counties in the Ili region of western Tianshan. The Ili region has a unique topography that slopes from east to west in a trumpet shape opening westward. This terrain blocks cold air from the Arctic Ocean and dry-cold/dry-hot airflows from the northeast and southeast, while the open western side facilitates the intrusion of warm westerly airflow from the Atlantic and Mediterranean, with precipitation increasing with elevation. This creates a climate with both mid-temperate continental characteristics and a relatively mild, humid "Jiangnan beyond the Great Wall" feature. The vertical zonation of mountain vegetation is distinct, with the montane coniferous forest zone dominated by Schrenk's spruce, mainly distributed on shady and semi-shady slopes at 1600–2700 m elevation as an evergreen shade-tolerant and cold-resistant species, with mountain gray-brown forest soil.

Sampling was conducted in October 2017. We primarily collected samples from fallen trees, obtaining 122 tree discs from 28 sample trees at six trunk heights (1.3 m, 5 m, 10 m, 15 m, 20 m, and 25 m). Additionally, we collected cores from healthy standing trees near the fallen trees to assist with cross-dating. All core samples were processed strictly following dendrochronological principles and procedures. After natural air-drying, samples were mounted, sanded, and polished, and then visually cross-dated. We used the LINTAB tree-ring width measurement system for width measurements and the COFECHA program for cross-dating quality control. The ARSTAN program was used to establish tree-ring width chronologies. Due to sample size limitations, we established standard tree-ring width chronologies for each trunk height (Figure 1) and conducted our research based on these chronologies.

1.2 Climate Data

In tree-ring based climate research, correlation analysis between tree-ring chronologies and meteorological factors is key to assessing whether the chronology can reflect climate information. The meteorological data used in this study include monthly precipitation and monthly mean temperature from 1961 to 2014 obtained from three meteorological stations: Tekes County (43°28 12 N, 81°46 12 E), Gongliu County (43°10 48 N, 82°13 48 E), and Xinyuan County (43°27 N, 83°18 E) (Figure 2). Precipitation in the study area is mainly concentrated from May to September, accounting for 29.83% of annual precipitation in July alone. The warmest month is July (20.60°C), while the coldest month is January (-9.01°C) (Figure 3).

1.3 Research Methods

We conducted correlation analysis between the measured standard tree-ring width chronologies at each trunk height and meteorological factors (monthly precipitation and monthly mean temperature) to determine the influence of meteorological factors on the radial growth of Schrenk' s spruce. To quantify the relationship between Schrenk' s spruce and mean temperature and precipitation, we performed multiple regression analysis using the monthly mean temperature and precipitation with the highest correlation coefficients for each trunk height, establishing multiple regression models for each height: $y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 +$, where y is the standardized tree-ring width index for each trunk height, x_1 and x_2 are the mean temperature and precipitation of the months most significantly correlated with each trunk height chronology, β_0 is the intercept, β_1 and β_2 are regression coefficients for temperature and precipitation, and is the error term.

To further analyze the contribution rates of mean temperature and precipitation to radial growth at different trunk heights, we selected the corresponding mean temperature and precipitation months with the greatest impact on each trunk height to construct multiple regression models. We used the relaimpo package to calculate absolute contribution rates (the sum of absolute contribution rates equals R^2, reflecting the explanatory power of each factor on radial growth) and relative contribution rates (the sum of relative contribution rates equals 1, reflecting the importance of each factor) to determine the absolute and relative contribution rates of mean temperature and precipitation at different trunk heights. Additionally, we used a fixed start year moving window method to calculate correlation coefficients between tree-ring width chronologies at different trunk heights of Schrenk' s spruce and meteorological factors, assessing the stability of relationships between radial growth at each trunk height and meteorological factors (moving window = 31 years).

2. Results and Analysis

2.1 Tree-Ring Chronology Analysis at Different Trunk Heights

Table 1 presents the statistical characteristics of tree-ring chronologies at different trunk heights. The chronologies show that the longest reliable chronology length is 230 years at the 1.3 m trunk height, and the shortest is 153 years at the 25 m trunk height. The first-order autocorrelation coefficients of tree-ring width chronologies at the six trunk heights range from 0.558 to 0.846, indicating that radial growth in the current year at each trunk height is significantly influenced by the previous year' s growth. The signal-to-noise ratio (SNR) is the ratio of climate signals to noise from non-climatic factors, with larger SNR values indicating more climate information in the chronology. Table 1 shows SNR values ranging from 10.714 to 37.714, indicating strong climate signals in all trunk height chronologies. The expressed population signal (EPS) values are all above 0.85, demonstrating that each trunk height chronology sequence has good representativeness of the population and high chronology quality.

Inter-correlation analysis among the six trunk height tree-ring width chronologies (Table 2) shows that the correlation between the 1.3 m trunk height and the 25 m trunk height is the lowest at 0.558, while correlations between other trunk heights are better. Analysis reveals that radial growth patterns are similar across different trunk heights of Schrenk' s spruce, and when correlating each trunk height with adjacent higher trunk height chronologies, the best correlations are always found with adjacent heights.

2.2 Correlation Between Tree-Ring Width Chronologies and Meteorological Factors at Each Trunk Height

Research indicates that autumn and winter meteorological factors have lag effects on tree-ring growth. Therefore, we selected meteorological factors from the previous year (September–December) and current year (January–December) for response and stability analysis (Figure 4). In correlation analysis between each trunk height and precipitation, all trunk heights show a significant positive correlation with September precipitation of the current year and a significant positive correlation with November precipitation of the previous year. Additionally, trunk heights of 5–25 m show a significant positive correlation with July precipitation of the current year, while the 1.3 m trunk height shows a significant negative correlation with June precipitation of the current year and a significant positive correlation with September precipitation of the previous year. The response to precipitation shows good consistency across trunk heights.

In correlation analysis with mean temperature, radial growth at all trunk heights is primarily influenced by November mean temperature of the previous year. Furthermore, September mean temperature of the previous year promotes radial growth at the 1.3 m trunk height, while December mean temperature of the previous year shows a significant negative correlation with trunk heights of 5–25 m ($r = -0.288$, $P < 0.05$). Comprehensive analysis shows that radial growth at the 1.3 m trunk height is mainly influenced by September mean temperature of the previous year and September precipitation of the current year, while trunk heights of 5-25 m are simultaneously influenced by July precipitation of the current year.

2.3 Contribution Rates of Mean Temperature and Precipitation to Radial Growth at Different Trunk Heights

To investigate the influence mechanisms of radial growth and meteorological factors at different trunk heights, we selected the mean temperature and precipitation months with the greatest impact on each trunk height to construct multiple regression models (Table 3). The results show that the months with highest correlation for mean temperature are consistently November of the previous year across all trunk heights, showing good uniformity. The months with highest correlation for precipitation are September of the current year for all trunk heights, except for the 1.3 m height where it is June of the current year. The variance in radial growth explained by mean temperature and precipitation differs across trunk heights, with R^2 values of 0.223, 0.284, 0.267, 0.271, 0.265, and 0.268 for 1.3 m, 5 m, 10 m, 15 m, 20 m, and 25 m heights, respectively.

We calculated the relative and absolute contribution rates of mean temperature and precipitation in each multiple regression model (Figure 5). The relative contribution rates of November mean temperature of the previous year and September precipitation of the current year are 72.02% and 27.98% at 1.3 m height, 54.26% and 45.74% at 5 m height, 35.69% and 64.31% at 10 m height, 40.37% and 59.63% at 15 m height, 50.73% and 49.27% at 20 m height, and 58.65% and 41.35% at 25 m height. The relative contribution rates of mean temperature are higher than precipitation at 1.3 m and 5 m heights, while precipitation contribution rates exceed temperature at higher trunk heights.

In terms of absolute contribution rates, mean temperature accounts for 15.24% at 1.3 m, 12.39% at 5 m, 10.63% at 10 m, 10.74% at 15 m, 7.50% at 20 m, and 8.39% at 25 m height. Precipitation absolute contribution rates are 4.67% at 1.3 m, 10.63% at 5 m, 19.35% at 10 m, 15.14% at 15 m, 12.85% at 20 m, and 14.71% at 25 m height. These results demonstrate that at the 1.3 m trunk height, both the relative and absolute contribution rates of mean temperature are higher than those of precipitation. As trunk height increases, precipitation contribution rates become higher than temperature contribution rates.

2.4 Moving Correlation Between Tree-Ring Width and Meteorological Factors at Each Trunk Height

Moving correlation analysis reveals that radial growth of Schrenk's spruce at different trunk heights shows dynamic responses to climate change (Figures 6 and 7). The moving correlation between each trunk height and precipitation shows that the correlation between the 1.3 m trunk height and September precipitation of the current year shifts from positive to negative, becoming significantly negative from the late 1990s onward. The 5 m trunk height shows a significant negative correlation with September precipitation of the current year, with the correlation gradually weakening from significant positive to non-significant. Both the 10 m and 15 m trunk heights exhibit unstable correlations with September precipitation of the current year. The correlation between the 20 m trunk height and September precipitation of the current year gradually weakens from significant positive to non-significant, while the 25 m trunk height shows a significant negative correlation with September precipitation of the current year that gradually strengthens.

The moving correlation between each trunk height and mean temperature shows that all trunk heights exhibit a significant negative correlation with December mean temperature of the previous year during 1961–1991 ($P < 0.05$). The negative correlation with December mean temperature of the previous year strengthens at all trunk heights, while the correlation with November mean temperature of the previous year gradually weakens. The correlation between June mean temperature of the current year and each trunk height gradually strengthens from 1961, showing a significant positive correlation from 1975–1991, and eventually converting to a non-significant relationship (1991–2014). The moving correlation shows that the sensitivity of each trunk height to June mean temperature of the current year has decreased in recent years, consistent with the divergence response results of Larix sibirica radial growth to climate change in the Altai Mountains by Jiao et al. Global warming has increased temperatures in high northern latitudes, gradually reducing temperature limitations on tree growth.

3.1 Comparative Analysis of Radial Growth-Climate Relationships at Different Trunk Heights from Point to Regional Scale

Our analysis shows that radial growth of Schrenk' s spruce (Picea schrenkiana) at different trunk heights is jointly influenced by mean temperature and precipitation. Zhang et al. conducted a study on the relationship between different trunk heights of Schrenk' s spruce and meteorological factors at a single point, finding that each trunk height (1.3 m, 5 m, 10 m, 15 m, 20 m, and 25 m) showed a significant positive correlation with November mean temperature of the previous year and a significant negative correlation with September precipitation of the current year. Our regional-scale study obtained the same results. When expanding from point to regional scale, we found that September precipitation of the current year is extremely significantly positively correlated with the 1.3 m trunk height but not significantly correlated with trunk heights of 5–25 m. The possible reason for the lack of significant relationship at 5–25 m heights may be influenced by tree canopy density. Chen et al. found that canopy shading has a cooling effect, which can reduce high-temperature damage and evapotranspiration, equivalent to increasing natural precipitation. The temperature at the 1.3 m trunk height may be lower than at other heights, not reaching the climatic conditions required for tree growth, thus causing the above results, but this specific mechanism requires further verification.

3.2 Differences in Contribution Rates of Mean Temperature and Precipitation at Different Trunk Heights

Analysis of relative and absolute contribution rates shows that radial growth of Schrenk' s spruce at different trunk heights in the Tianshan Mountains is inconsistently affected by mean temperature and precipitation. At the 1.3 m trunk height, the contribution rate of mean temperature is higher than that of precipitation, indicating that tree growth at this height is more temperature-limited than at higher trunk heights. At trunk heights of 10 m and above, the contribution rate of precipitation exceeds that of mean temperature, indicating that as trunk height increases, the promoting effect of precipitation on radial growth strengthens. Zhang et al. reached similar conclusions in their study of Korean pine (Pinus koraiensis) in Changbai Mountain. It is generally believed that temperature is the limiting factor for radial growth at the upper forest limit, while precipitation is the main limiting factor at the lower forest limit, but altitudinal gradients for tree growth differ conceptually from treating the entire trunk as an independent unit for climate research.

Based on the pipe model hypothesis, the trunk is formed by bundles of unit pipes that function as both water conduction organs and mechanical support. During water transport throughout the trunk, radial diffusion capacity decreases with increasing trunk height. Additionally, studies have shown that water moves in a counterclockwise spiral pattern during longitudinal transport in conifers, with resistance increasing as water moves upward from the base, resulting in relatively less water at the top. Under water deficit conditions, plant leaf stomata close to reduce transpiration, decreasing photosynthetic rate. During water transport, the base has relatively abundant water content compared to other trunk positions, where rising temperatures can promote radial growth. As water moves upward and gradually decreases, precipitation becomes the key limiting factor affecting growth at other trunk positions.

3.3 Dynamic Response of Radial Growth at Different Trunk Heights of Schrenk' s Spruce to Climate Change

Moving correlation analysis between each trunk height of Schrenk' s spruce and meteorological factors shows that radial growth at different trunk heights has produced dynamic responses to climate change, with varying degrees of response among trunk heights. The sensitivity of each trunk height to June mean temperature of the current year has decreased in recent years, consistent with the divergence response results for Larix sibirica in the Altai Mountains by Jiao et al. Global warming has caused temperature increases in high northern latitudes, gradually reducing temperature limitations on tree growth. Meanwhile, the sensitivity to December mean temperature of the previous year has strengthened (negative correlation enhanced). Precipitation in the study area has declined since the 1990s, potentially causing drought-induced growth inhibition. The moving correlation shows an overall decreasing trend between November mean temperature of the previous year and each trunk height, indicating that the promoting effect of mean temperature on radial growth is weakening. Some studies suggest that low winter temperatures are a driving factor for plant cell formation, and low temperatures in autumn and winter are important for breaking bud dormancy, after which higher spring temperatures can promote bud growth. The moving correlation shows that the sensitivity of the 1.3 m trunk height to September precipitation of the current year has strengthened (converting to a significant negative correlation), indicating that September precipitation has an inhibitory effect on radial growth. September is at the end of the growing season, when lower temperatures and increased cloud cover reduce solar radiation, decreasing photosynthetic rates, and higher precipitation further hinders organic matter synthesis and accumulation, which is unfavorable for radial growth, thus showing a significant negative correlation.

4. Conclusions

Based on the analysis of tree-ring width chronologies at different trunk heights of Schrenk' s spruce in the Ili mountainous region, we conclude:

1. Schrenk' s spruce at different trunk heights shows similar radial growth patterns, jointly affected by mean temperature and precipitation. Specifically, the 1.3 m trunk height is influenced by September precipitation of the current year and November mean temperature of the previous year, while trunk heights of 5–25 m are simultaneously influenced by July precipitation of the current year.

2. Through contribution rate analysis, radial growth at the 1.3 m trunk height is primarily temperature-limited, while at trunk heights of 10 m and above, it is primarily precipitation-limited.

3. Dynamic responses to climate change differ among trunk heights, mainly showing that correlations with December mean temperature of the previous year weaken, correlations with June mean temperature of the current year first strengthen then weaken, negative correlations with September mean temperature of the previous year strengthen, negative correlations with September precipitation of the current year strengthen at 1.3 m, 5 m, 10 m, and 15 m heights, and correlations with January precipitation weaken at 10 m, 15 m, 20 m, and 25 m heights.

4. To improve tree-ring climate response and reconstruction accuracy, higher trunk height samples could be considered for inclusion in sampling ranges when field conditions permit. Quantifying the relationship between radial growth at different trunk heights and meteorological factors helps understand differential climate responses across heights and provides a foundation for more accurate climate reconstruction.

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