Climate Change-Induced Growth Decline in Planted Forests of Quercus variabilis Blume near Beijing, China

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Abstract: A progressive decline in tree growth may be induced by global warming, affecting tree health and eventually resulting in death, particularly for trees growing in rocky mountainous regions where seasonal droughts have become more pronounced. However, tree growth dynamics in areas experiencing pronounced climate change have received little attention. In this study, a total of 100 (10 m × 10 m) grid plots were investigated in planted forests of Chinese cork oak (Quercus variabilis Blume), which were established in the 1960s and 1970s in a rocky mountainous area near Beijing, northern China. Furthermore, the radial growth of Q. variabilis (a total of 843 trees sampled from the dominant [D], co-dominant [CD], and suppressed [S] crown classes) was analyzed using retrospective dendrochronology and generalized additive models. The effects of meteorological changes between 1962 and 2020 on radial growth across the three crown classes were examined using correlation analysis. The results indicated that the growth of Q. variabilis initially increased and then decreased after 2010 at the regional level, and these trends varied according to crown class. The radial growth of the D trees responded more positively to an increase in temperature and drought severity index (<0 for dry and >0 for wet conditions) compared with that of the CD and S trees. The growth of the D and CD trees continuously increased under higher temperatures during the rainy seasons (June to September); however, the increases were higher for D than for CD trees. In contrast, the radial growth of S trees declined. We confirmed the historical effects of rising temperatures on tree growth and health, which are linked to water availability. Our data suggested that Q. variabilis trees will be considerably affected by intensified droughts. This study furthers our knowledge regarding the impact of climate change on tree and forest growth and provides management strategies for afforestation projects in rocky mountainous areas that are facing climate change.

Keywords: climatic variables; radial growth; deciduous tree; forest plantation; rocky mountainous area

1. Introduction

Understanding the responses of forest ecosystems to global warming is an emerging and serious concern. This is particularly true for forest ecosystems in rocky mountainous areas, where seasonal droughts may be more evident. In addition, global temperatures have increased over the last 100 years, particularly since the 1980s. Planted forests are more abundant than other forest types in China [1]. As essential constituents of regional and global climate systems, planted forests contribute to carbon balance and the water cycle [2, 3] and provide a wide range of ecosystem services to local populations. Most planted forests are widely distributed in mountainous areas because of their limited geographical conditions. However, large-scale forests planted in rocky mountainous areas often exhibit low growth rates, diminished tree stability and resilience, and poor quality of the dominant trees [4, 5] because of frequent seasonal droughts. Therefore, foresters, ecologists, and land managers
have increasingly focused on strategies to improve the quality of planted forests in rocky mountainous regions because of climate change.

Tree growth and dynamics are mainly governed by meteorological factors (temperature, precipitation, and drought severity). Recent studies have focused primarily on the impact of climate variables on physiological responses versus the characteristics of tree species [6], soil properties [7–9], and community structures (i.e., density, composition, and species competition) [10,11]. For example, Luo et al. (2017) noted that rising air temperatures can increase the decomposition rate of soil organic matter and stimulate the absorption of essential nutrients such as C, N, P, and K [12]. Moreover, warmer air temperatures versus rising atmospheric CO₂ concentrations increase plant photosynthesis and water-holding capacity, further increasing the accumulation of above- and below-ground biomass [13]. Meanwhile, these impacts may alter species composition and distribution. For instance, rising temperatures promote population growth at high altitudes; in contrast, forest ecosystems at lower elevations exhibit a decline in growth because of frequent seasonal droughts, resulting in range contraction [14–16]. A rocky mountainous area at low altitude is often characterized by thin soils and a high gravel content with strong seasonality [17,18], which results in insufficient water availability for tree growth during the growing season. The frequency of seasonal droughts in rocky mountainous areas may be one of the main factors affecting the growth and development of planted trees under climate warming. However, there remains a notable gap in the research on the adaptation of pure-planted forests to climate change in seasonal drought areas. Thus, to explore the climatic driving forces of the decline in planted forests, systematic research must be performed to evaluate the effects of meteorological factors on the radial growth of trees in this region.

The Chinese cork oak (Quercus variabilis Blume), a fast-growing deciduous species, is widely distributed throughout Eastern Asia (24°–42° N, 97°–140° E) and commonly grows on sunny slopes at low altitudes (<800 m a.s.l.). Considering its adaptability, rapid growth, and drought tolerance, Q. variabilis is commonly used for afforestation in mountainous areas of China, benefiting the ecology, economy, and culture of local populations. However, the distribution range of planted forests of Q. variabilis has diminished, and their growth may have declined under recent progressive seasonal droughts [19–21]; nevertheless, the radial growth of Q. variabilis in this region, which is sensitive to meteorological factors, remains unclear. Therefore, understanding the impacts of climate on the growth and quality of Q. variabilis plantations is essential for designing appropriate forest management strategies for rocky mountainous areas.

To date, existing studies on the response of oak trees to climate change have been conducted on healthy individuals. We hypothesized that trees with various signs of vigor may exhibit distinct sensitivity to climate variables. This study aimed to determine whether climate change considerably affects tree growth in planted forests and which meteorological factors are considered the main driving forces of tree decline in seasonal drought areas. Thus, we investigated the radial growth of Q. variabilis in three vigor classes (dominant [D], co-dominant [CD], and suppressed [S] trees) and explored how the classes were related to climate change using correlation coefficient analysis. The main objectives of this study were to (i) analyze the temporal radial growth of Q. variabilis in the three crown classes; (ii) determine whether the growth of planted forests of Q. variabilis is affected by changing climatic conditions, including rising temperatures and seasonal droughts; and (iii) propose implications for improving the negative effects of global warming on planted forests in rocky mountainous areas. This study will help us identify the mechanisms by which meteorological factors affect the growth of the Q. variabilis plantations in seasonal drought areas.

2. Materials and Methods
2.1. Site Description

The research was conducted in the Xishan National Forest Park (39°58'18.17” N, 116°11’51.20” E), which is situated in a mountainous area in the north of China (Figure 1).
The study site is located 30 km away from Beijing at an average elevation of 450 m a.s.l., and it experiences a hot, rainy summer and a cold, dry winter. The climate of the area is warm temperate with continental monsoons and strong seasonality. Approximately 90% of the 465 mm precipitation occurs during the growing season, with the majority concentrated in July and August. In this region, the growing season generally continues for approximately 240 days, from April to the end of November, whereas the non-growing season lasts for 180 days. The site is relatively flat, and the soil is shallow (with a depth of 0.3–0.8 m), rocky, and rich in clay. The soil has a high soil humus content in the upper layers and high gravel density in the lower layers. As a typical lithoid mountainous area, it has pure artificial forest plantations near Beijing, northern China. Note: Sampling plots were located at the study site (red symbol).

2.2. Climate Data

Meteorological data of the research site covering the period 1962–2020, including annual maximum temperature (T\textsubscript{max}), mean temperature (T\textsubscript{mean}), minimum temperature (T\textsubscript{min}), precipitation (PPT), Standardized Precipitation Evapotranspiration Index in 12 months (SPEI 12 MONTHS), and Palmer Drought Severity Index in 12 months (PDSI 12 MONTHS), were derived from the World Meteorological Organization (http://climexp.knmi.nl/), URL (accessed on 5 October 2022). SPEI 12 MONTHS and PDSI 12 MONTHS are good indicators of drought severity that consider the effects of other climatic factors, such as temperature and wind [22,23]. Therefore, long-term SPEI 12 MONTHS and PDSI 12 MONTHS are used as alternatives to water availability in the study area. Positive PDSI 12 MONTHS and SPEI 12 MONTHS values are often regarded to be indicative of wet climates, whereas negative values indicate dry climates (<0 for dry and >0 for wet conditions).

According to climate data from 1962 to 2020, the temperatures (T\textsubscript{max}, T\textsubscript{mean}, and T\textsubscript{min}) showed a consistent increase trend with annual variation, which was particularly evident after 1980. Conversely, SPEI 12 MONTHS and PDSI 12 MONTHS decreased considerably over time, and a weak downtrend in PPT was observed (p < 0.001). Overall, climate warming and drought severity drastically increased with time at the study site (Figure 2). The annual evapotranspiration is approximately 1100 mm. The area has a mean annual air temperature of 11.6 °C with 2662 h of annual sunshine and a mean monthly air temperature of −3.4 °C in December and 26.7 °C in July. It often experiences long-term droughts because of the uneven rainfall distribution, and <15 mm PPT was recorded in the non-growing
season (December of the previous year to March of the current year), with lower SPEI 12 MONTHS and PDSI 12 MONTHS values (Figure 3).

Figure 2. Annual variations in meteorological factors at the study site during 1962–2020 period. $T_{\text{max}}$—maximum temperature (a); $T_{\text{mean}}$—mean temperature (b); $T_{\text{min}}$—minimum temperature (c); PPT—precipitation (d); SPEI 12 MONTHS—Standardized Precipitation Evapotranspiration Index in 12 months (e); and PDSI 12 MONTHS—Palmer Drought Severity Index in 12 months (f).

Figure 3. Monthly variations in meteorological factors at the study site during 1962–2020. A—April; M—May; J—June; J—July; A—August; S—September; O—October; N—November; D—December; J—January; F—February; M—March; GS—growing season; NGS—non-growing season; $T_{\text{max}}$—maximum temperature (a); $T_{\text{mean}}$—mean temperature (b); $T_{\text{min}}$—minimum temperature (c); PPT—precipitation (d); SPEI 12 MONTHS—Standardized Precipitation Evapotranspiration Index in 12 months (e); and PDSI 12 MONTHS—Palmer Drought Severity Index in 12 months (f).

We calculated climate anomalies to evaluate the meteorological factors that drive temporal changes in tree growth. These anomalies were identified as a departure of the mean between two sequential measurements from the long-term climate mean [24]. Six sets of climate anomalies were calculated: annual $T_{\text{max}}$, $T_{\text{mean}}$, $T_{\text{min}}$, PPT, SPEI 12 MONTHS, and PDSI 12 MONTHS.
2.3. Forest Inventory Data

Fieldwork was conducted from July to September 2021. At the study site, a total of 100 sampling plots (10 m × 10 m) were established, with a minimum distance of 40 m between each plot (Figure 1). The criteria for plot selection were as follows: (a) the plots were situated at least 100 m away from openings to avoid edge effects; (b) the stand conditions were relatively homogeneous in structure and composition with no anthropogenic disturbances (i.e., wood cutting, thinning, pruning, camping, or grazing); and (c) all plots were located in areas with the same topography, aspect, and slope.

At each plot, trees with a diameter at breast height (DBH) ≥ 4 cm were identified, measured, and recorded, including species, size (DBH), location (x–y coordinates), height, and crown class. The crown classes were categorized into three groups based on tree vitality (D, CD, and S trees). In this study, D trees had crowns located above the main forest layers, CD trees had crowns equal to those in the main forest layers, and S trees had crowns located below the main forest layers [25,26]. At each plot, 3–4 trees were cut and felled to collect tree ring disks. In total, 864 trees were sampled for dendroecological analyses. Each sampled tree was stem-sectioned at 0 m (stem base), at a height of 1.3 m, and at intervals of 2 m above the DBH along the remaining length of the stem. In this study, disks sectioned at the stem base were used. The stem disks were air-dried, progressively sanded, and polished using fine sandpaper until the tree rings were clearly visible, after which they were scanned at high resolution (1200 dpi) [27,28]. Furthermore, the tree ring widths (0.001 mm), consisting of the earlywood (EW) and latewood (LW) widths of each stem disk, were gauged along two (south and north) or four (south, north, east, and west) lines from the core to the pith using the software WinDENDRO STD 4800 (Regent Instruments Inc., Québec City, QC, Canada, 2009). We identified the interannual ring as the boundary between light-colored earlywood and dark-colored latewood. All the ring width series were calibrated via cross-dating using the program COFECHA v6.06P [29]. Samples of poor quality (low COFECHA correlation coefficients) were removed from the subsequent analyses. Finally, we obtained an extensive dataset comprising 100 plots with 843 Q. variabilis trees categorized into the D (212 trees), CD (315 trees), and S (316 trees) classes, providing a rich source of data for examining the interaction between tree radial growth and climate variables. We acknowledge the significant impact of the data collection on the environment and regret the necessity of cutting down trees to obtain the ring width data. Specific sample information is presented in Table 1. The earlywood width (EW) and latewood width (LW) of the corresponding years in two or four directions of each stem disk were averaged, and the radial growth of each tree was expressed as the basal area increment (BAI, annual increment in tree ring area). The age of the trees in the core sample ranged from 36 to 58 years.

<table>
<thead>
<tr>
<th>Crown Classes</th>
<th>Period</th>
<th>No. of Trees (Disks)</th>
<th>Ave. Age (a)</th>
<th>Ave. DBH (cm)</th>
<th>Ave. TH (m)</th>
<th>Ave. CD (m)</th>
<th>Ave. BAI (cm²/year)</th>
<th>Ave. EW (cm/year)</th>
<th>Ave. LW (cm/year)</th>
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<tr>
<td>D</td>
<td>1962–2020</td>
<td>213/212</td>
<td>47</td>
<td>20.2</td>
<td>15.8</td>
<td>5.23</td>
<td>17.05</td>
<td>0.361</td>
<td>1.230</td>
</tr>
<tr>
<td>CD</td>
<td>1970–2020</td>
<td>320/315</td>
<td>45</td>
<td>17.9</td>
<td>13.7</td>
<td>3.52</td>
<td>15.71</td>
<td>0.355</td>
<td>1.156</td>
</tr>
<tr>
<td>S</td>
<td>1979–2020</td>
<td>331/316</td>
<td>38</td>
<td>14.7</td>
<td>10.3</td>
<td>2.23</td>
<td>12.15</td>
<td>0.341</td>
<td>1.116</td>
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</table>

Table 1. Statistical information for dominant (D), co-dominant (CD), and suppressed (S) trees in the sampled Quercus variabilis. No.—number; Ave.—average; DBH—diameter at breast height; TH—tree height; CD—crown diameter; BAI—basal area increment; EW—earlywood width; LW—latewood width.
2.4. Data Processing

2.4.1. Hegyi Competition Index

The Hegyi competition index [30] was modified to capture the impact of intraspecific competition on tree growth.

\[ H_{ijk} = \left[ \exp \left( \frac{\text{maxDBH}_{ijk} - \text{DBH}_{ijk}}{\text{maxDBH}_{ijk} - \text{minDBH}_{ijk}} \right) \right]^\alpha \times \sum_{n \neq i} \frac{\text{DBH}_{njk}}{\left[ (\text{Distance})_{inj} \right]^\beta} \]  

where \( i, n, j, \) and \( k \) are the \( i \)th subject tree, \( n \)th neighboring tree, \( j \)th census, and \( k \)th plot, respectively. Here, \( N \) is the number of trees per plot. \( \text{maxDBH}_{ijk} \) and \( \text{minDBH}_{ijk} \) are the maximum and minimum DBH at the \( j \)th census in plot \( k \), respectively. \( \text{DBH}_{ijk} \) and \( \text{DBH}_{njk} \) are the DBH of the focal and neighboring trees, respectively. \( (\text{Distance})_{inj} \) is the distance between trees \( i \) and \( n \) at the \( j \)th census in the \( k \)th plot. \( \alpha \) and \( \beta \) are the cross-stand asymmetric coefficient and the crowdedness coefficient, respectively.

2.4.2. Tree Growth

The radiating ring was derived from the mean ring widths measured in four distinct directions on each disk sample, and the annual BAI was computed based on the following model:

\[ \text{BAI} = \pi \times \left( R_n^2 - R_{n-1}^2 \right) \]  

where \( R_n \) and \( R_{n-1} \) denote the tree radius at breast height in the current year (\( n \)) and the previous year (\( n-1 \)) of ring formation, respectively [31].

To detect temporal trends in BAI, EW, and LW, we developed Year models using generalized additive models (GAMs) based on calendar year, ontogeny, competition, and their two-way interactions on tree growth. Because tree age (A), tree size (DBH), and Hegyi competition (H) strongly affected tree growth, they were considered to account for the effects of the exogenous and endogenous processes associated with forest development on the growth of various crown classes (i.e., D, CD, and S). To examine the long-term temporal trends in the tree growth of the various crown classes, we fitted the GAMs to include the main effects of Year, A, DBH, and H and their two-way interactions (Equation (3)). The first model was developed for all sampled trees and included three hierarchical layers in the dataset, i.e., observations nested in trees, trees nested in plots, and plots nested in class groups. Here, the temporal trends of the annual BAI, EW, and LW in the three crown classes were compared to assess the classes promoting the decline in forest growth. The trends in BAI, EW, and LW were modeled as smoothing functions of the temporal variations, expressed as years. A, DBH, and H were included as random effects in the model to account for intra-annual variations. In general, the GAMs were used to assess the relationship of the calendar year with BAI, EW, and LW in different vigor classes (i.e., D, CD, and S), which accounted for A, DBH, and H, to remove the effects of endogenous and exogenous processes on tree growth. The final model is expressed as follows:

\[ \begin{align*}
(\text{BAI}, \text{EW}, \text{LW})_{ijkg} & = \beta_0 + \beta_1 \text{Year}_{ijkg} + \delta_1 f(A) + \delta_2 f(DBH) + \delta_3 f(H) \\
& + \delta_4 \text{Year}_{ijkg} \times f(A) + \delta_5 \text{Year}_{ijkg} \times f(DBH) \\
& + \delta_6 \text{Year}_{ijkg} \times f(H) + \delta_7 f(A) \times f(DBH) \\
& + \delta_8 f(A) \times f(H) + \delta_9 f(DBH) \times f(H) + \varepsilon_i
\end{align*} \]

where \( i, j, \) and \( k \) are the \( i \)th census period observation for \( j \)th tree in the \( k \)th plot of the \( g \)th class group; \( \beta_0 \) is the smoothing function; \( \beta_1 \) is the intercept of the model; \( \delta_n \) is the fixed coefficient to be estimated; and \( f \) is a spline function fitted to each individual time series (average BAI, EW, and LW of all D, CD, and S trees). In this study, the two-way interactions of A, DBH, and H with tree growth were modeled simultaneously. To examine the temporal growth trends, analyses were extended to the D, CD, and S trees. Based on these models, the class group was not specified in Equation (3).
We also fitted nonlinear mixed-effect models to explore the temporal trends in radial growth (BAI in cm²/year and EW and LW in cm/year) and comparatively examine the growth patterns of *Q. variabilis* in the three vigor classes. For climate–growth interactions, Spearman’s correlation coefficients were calculated between the climate anomalies and radial growth (BAI, EW, and LW) to comparatively analyze the responses of the D, CD, and S trees to climate drivers (statistical significance was set at *p* < 0.05, and a higher significance was set at *p* < 0.01). The data analysis was performed in R 4.2.2 (R Core Team, 2022) using the packages “data table” and “dplyr”, and the GAMs were fitted using the “mgcv” package. The location map of the sampling plots was generated using ArcGIS 10.9 (Esri, Redlands, CA, USA, 2021), and the other figures were produced using OriginPro v2022 9.9.0.225 (OriginLab Corp., Northampton, MA, USA, 2022).

3. Results

3.1. Temporal Changes in Tree Growth

In this study, the temporal changes in BAI, EW, and LW were analyzed using GAMs (Figure 4). Over 60 years, the BAI of *Q. variabilis* forest increased drastically but stagnated after 2010; however, these trends varied among the three crown classes (Figure 4a). The BAI of the D trees showed a continuously increasing trend during 1962–2020, whereas that of the CD trees started to decrease after 2010. In contrast, the BAI of the S trees has been constrained since the early 2000s, and their growth status is consistently lower than that of the other two classes.

![Figure 4](image_url)

**Figure 4.** Predicted temporal trends in (a) basal area increment (BAI), (b) earlywood width (EW), and (c) latewood width (LW). Blue dots represent the temporal trends in BAI, EW, and LW during 1962–2020; the red curves represent the fitted linear line and 95% confidence intervals summarized from GAMs (detailed in the Materials and Methods section).
Q. variabilis growing in this area demonstrated a narrow EW and a wide LW because it was affected by seasonal climatic factors. To quantify the annual evolution of radial growth in the three crown classes, the EW and LW were plotted against time (Figure 4b,c). For 60 years, the EW and LW of all the trees initially increased and then decreased after 2010; however, these trends varied among the three crown classes (Figure 4). Similar to BAI, the EW in the D trees continuously increased from 1962 to 2020, whereas that in the CD trees decreased after 2010 and decreased in the S trees after the early 1990s (Figure 4b). However, the LW in the D and CD trees sharply increased, whereas in the S trees, it decreased after 2015 (Figure 4c). These results indicate that the temporal change in EW contributed more to the decline in growth of Q. variabilis than the temporal change in LW in this region.

3.2. Effects of Meteorological Factors on Tree Growth

3.2.1. Effects of Climate Variables on BAI

For the three crown classes of Q. variabilis, the responses of BAI growth to climate change were investigated ($p < 0.05$) (Figure 5). The BAIs of the three crown classes were strongly and positively correlated with $T_{\text{mean}}$ and $T_{\text{min}}$ in almost every month. However, different results were obtained for the effect of $T_{\text{max}}$ on BAI for the three crown classes. The BAI in the D and CD trees exhibited a significantly positive correlation with $T_{\text{max}}$ during the growing season, whereas the BAI in the S trees exhibited a significantly negative correlation with high temperature in the late non-growing (March) and early growing seasons (April and May). Additionally, the positive correlation coefficients were higher for the D trees than for the other classes, particularly from July to September. Significantly positive correlations were found between the BAI and PPT during the growing season, and the D tree responses were relatively significant in July and September. Similarly, the responses of BAI to SPEI 12 MONTHS and PDSI 12 MONTHS demonstrated significant differences among the three crown classes. SPEI 12 MONTHS was positively correlated with BAI in the D and CD trees in the hot summer (June to August), whereas no significant effects were found for the S trees in any of the months. Although PDSI 12 MONTHS positively affected the radial growth of Q. variabilis, some variations were observed across the different crown classes; specifically, PDSI 12 MONTHS had an obvious positive effect on BAI in the D and CD trees, and the D trees were more strongly positive than the CD trees. Similar to SPEI 12 MONTHS, weak correlations were observed between BAI and the PDSI during the whole year ($p < 0.05$) (Figure 5). We hypothesized that, in general, higher temperatures during drought seasons are the most dominant factors driving the differentiation of tree growth and quality in planted forests.

3.2.2. Effects of Climate Variables on EW and LW

Correlation analysis revealed that the growth of EW and LW in Q. variabilis was significantly affected by climate variables (Figure 6). For the three crown classes, similar patterns of radial growth (EW and LW) according to $T_{\text{mean}}$ and $T_{\text{min}}$ were identified. For instance, strong and significantly positive growth–climate correlations were observed for almost every month. However, significant variations in the growth response to $T_{\text{max}}$ were observed among the three crown classes (Figure 6). The EW and LW in the D trees were positively correlated with $T_{\text{max}}$ during the growing season (June to August), and the correlation coefficients were higher for LW ($p < 0.01$) than for EW ($p < 0.05$) during July and August. For the CD trees, LW was significantly positively correlated with $T_{\text{max}}$ during the growing season (July–September), but the correlation coefficients were lower than those for the D trees. In contrast to the D and CD trees, significantly negative patterns were found in the EW of the S trees from February to June (late non-growing and early growing seasons) ($p < 0.05$ and $p < 0.01$). Moreover, the EW of the S trees was more strongly restricted by $T_{\text{max}}$ during the early growing season than during the late non-growing season.
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Furthermore, the responses of EW and LW in the three crown classes to PPT, SPEI 12 MONTHS, and PDSI 12 MONTHS were analyzed ($p < 0.05$) (Figure 6). There were significant patterns in the EW and LW responses to PPT during the growing seasons, and the D tree responses were more significant than those of the other classes ($p < 0.01$). For the D and CD trees, SPEI 12 MONTHS was significantly positively correlated with EW and LW in the growing season (July–September), and the correlation coefficients were higher in D than in CD trees; in particular, SPEI 12 MONTHS in August strongly accelerated the growth of the LW in the D and CD trees ($p < 0.01$). However, weak correlations were observed between SPEI 12 MONTHS and the radial growth (EW and LW) of the S trees throughout the year. The EW and LW in the three crown classes were positively sensitive to PDSI 12 MONTHS for the entire year, but the correlation coefficients exhibited some differences across the three classes ($p < 0.05$). The EW and LW in the D trees were more strongly correlated with PDSI 12 MONTHS every month ($p < 0.01$), whereas only the LW in the CD trees was significantly sensitive to PDSI 12 MONTHS ($p < 0.05$). Nevertheless, low correlation coefficients were found between the radial growth (EW and LW) of the S trees and PDSI 12 MONTHS throughout the year. The results indicated that high temperatures under drought stress were more obviously impactful on the EW than on the LW of Q. variabilis in the lithoid mountainous area; moreover, double rings (EW and LW) of the D and CD trees continuously grew under high water availability, whereas the S trees exhibited no response.
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Figure 6. Relationship between the ring widths (EW and LW) and climate anomalies. EW—earlywood width; LW—latewood width; A—April; M—May; J—June; J—July; A—August; S—September; O—October; N—November; D—December; J—January; F—February; M—March; GS—growing season; NGS—non-growing season; Tmax—maximum temperature; Tmean—mean temperature; Tmin—minimum temperature; PPT—precipitation; SPEI 12 MONTHS—Standardized Precipitation Evapotranspiration Index in 12 months; and PDSI 12 MONTHS—Palmer Drought Severity Index in 12 months. * = correlation is significant at the 0.05 level, and ** = correlation is significant at the 0.01 level.

4. Discussion

4.1. Variations in Meteorological Conditions

Climatic variations are major natural factors influencing plant growth and survival in seasonal drought regions [32]. The study area, which is situated at low elevations in the lithoid mountainous area near Beijing, is a typical seasonal drought region in northern China [33]. Our investigation showed that the temperatures in this area rose by $0.035 \degree C$/year from 1962 to 2020, which is relatively higher than the overall rate in China ($0.025 \degree C$/year) and worldwide ($0.013 \degree C$/year) [34]. An irregular rise in air temperature can enhance soil evapotranspiration and water shortages [35]. The study area had high summer precipitation and low winter precipitation during the cold winter ($p < 0.01$). These results imply that the climate was in contrast to that in previous studies focusing on Mediterranean regions [36,37] and northwest Iberia [38]. Further, we observed that the vigorous growth of this forest can span 6–7 months each year, and the legacy effects of low precipitation in the non-growing seasons (24.5 mm) strengthened the drought severity in the early growing season (April and May). Therefore, the study area has often experienced long-term seasonal droughts. The long-term insufficient soil water availability caused by climate warming may be a critical factor that restricts tree growth because limited water input influences the physiological activities of plants (such as leaf photosynthesis, water
potential, and hydrologic conductivity). Consequently, several trees with developed root systems can grow depending on limited water availability, whereas vulnerable trees face severe decline because of insufficient water absorption [33]. Hence, climate change may drastically affect the growth and quality of the planted forests in this area.

4.2. Radial Growth of Q. variabilis

Growth slowing was observed in most trees before the decline, which was illustrated by an increase in annual autocorrelation and a change in the variables of the time series [39–41]. Based on our observations, Q. variabilis germinates at the beginning of April, loses its leaves at the end of November, and grows vigorously in summer (June to September). Moreover, we found that Q. variabilis comprises wide LW and narrow EW vessels. This finding is contrary to that of oak trees in northern and western Spain, which are known to foster wide EW and narrow LW vessels [38,42,43]. Consequently, the distinction between EW and LW is straightforward, and the tree ring compartment appears to undergo various climate-associated changes [44–46]. In this study, yearly variations in the BAI, EW, and LW of Q. variabilis were revealed, initially increasing rapidly with time and then decreasing after 2010, and the changing trend in EW was consistent with that in BAI. Moreover, EW decreased earlier than LW. This result was consistent with the radial growth of Q. variabilis in Ji Yuan, northern China [26]. EW formation contributed more to the declining growth of Q. variabilis. In addition, various trends in radial growth were observed across the three vigor classes. The growth of the D trees was continuous, whereas the growth of the CD and S trees decreased after 1990. In particular, the S trees exhibited a decline earlier than the CD trees. One hypothesis may be that the limiting factors substantially varied across the three crown classes, and the study area covered rainy, hot summers and dry, cold winters, which significantly affected the formation of ring wood in the trees. Previous studies have revealed that a temperature rise can stimulate xylem formation by extending the growing seasons or causing them to begin earlier [47]. However, the impact of high temperatures may weaken during seasonal droughts because drought severity increases to a threshold that negates the positive effects of increasing temperature. Moreover, wood formation was not completed at the same time each year, and the duration of formation varied [48]. Based on previous studies, the radial growth response of oak trees can record climatic changes, particularly its response to rainfall in the summer [49]. Similarly, our study revealed that high precipitation during the hot summer drastically stimulates LW formation, whereas low water availability during cold winter had negative effects on EW formation. Therefore, climate change may be critical in restricting the growth of Q. variabilis.

4.3. Climate–Growth Relationships

In addition to geophysical and edaphic factors, climate change influences radial growth and development in planted forests. In this study, the temperatures exhibited a significant effect on the radial growth of Q. variabilis, where the radial growth increased sharply at mean and minimum temperatures. Similar to our findings, previous studies on boreal tree species, such as Pinus sylvestris and Pinus nigra in east–central Spain and Picea mariana and Pinus banksiana in eastern Canada, observed a positive correlation between growth and temperatures [13,50,51]. In contrast, Gao et al. (2018) reported that the growth of Q. variabilis in the subtropical humid monsoon climate zone was negatively sensitive to temperature [20]. Moreover, Tardif et al. (2010) illustrated that the growth of Q. alba and Q. rubra at the northern limit of their distribution was confined to low temperatures [52]. These results indicate that limiting factors differ across various climate zones and not just by tree species. The radial growth of Q. variabilis was also significantly sensitive to PPT, SPEI 12 MONTHS, and PDSI 12 MONTHS. Higher precipitation and water availability increased the growth of Q. variabilis. Similarly, a study demonstrated a positive correlation between tree growth and wet weather at the northern and southern boundaries of the distribution of Pilgerodendron uviferum [53]. A recent study revealed that rising temperatures restricted tree growth at low elevations, particularly through impacts on soil evaporation.
and water use [54]. For *Q. variabilis*, 79% of the primary root system is strongly developed and homogeneously distributed in various soil layers [33], making it suitable for many water sources. Planted forests of *Q. variabilis* in this region may opportunistically increase their growth when water availability is sufficient, but there were variations in climate sensitivity among different crown classes.

Many studies have indicated the impact of climate change on several species in the same vigor class but have not performed comparison analyses on the sensitivity of various vigor classes to climate change. In this study, we found that climate change affected D, CD, and S trees. The radial growth (BAI, EW, and LW) of the D and CD trees continuously increased under high temperatures, whereas the S trees showed a reduction from February of the previous year to May of the current year. The growth of *Q. variabilis* remained significantly sensitive to precipitation during the growing season, and the responses of the D trees were more significant than those of the CD and S trees. Moreover, our study showed a higher positive sensitivity of D trees to SPEI 12 MONTHS and PDSI 12 MONTHS than CD trees, but S trees were not significantly influenced by these drought severity parameters throughout the whole year. Jia et al. (2022) found a typical pattern for *Q. variabilis* subject to frequent drought events, where there was a higher percentage of stored nonstructural carbohydrates consumed during drought events. This resulted in a significantly positive relationship between resistance and intrinsic efficient water use [26], which further limited tree growth following drought [55,56]. Previous studies in Mediterranean regions were characterized by less rainfall and high air temperatures in summer [57,58], which were contrary to our study parameters, but similar tree growth responses to PPT. Similar to other studies on oak tree species [59,60], our results demonstrated the overriding importance of meteorological factors for the radial growth of EW and LW in planted forests of *Q. variabilis*. Based on our results, we observed that the radial growth of *Q. variabilis* usually peaks in the rainy season, and it fosters wide LW vessels, whereas EW mostly comprises narrow vessels that are fostered during the spring. The distinction between EW and LW was evident because their tree ring compartments appeared to undergo various climate-associated changes. Considerable research has also demonstrated that trees may accumulate a larger proportion of nonstructural carbohydrates through photosynthesis under drought conditions, which are used to maintain respiration in the dormant season and the growth of EW in the following year. To further clarify which climatic variables induced the growth decline in *Q. variabilis* in the rocky mountainous regions, we compared and analyzed the responses of EW and LW to climate changes across the three crown classes. We observed that the EW and LW of the S trees were limited by high temperatures in the late non-growing and early growing seasons, whereas the D and CD trees continuously grew. Moreover, the EW and LW of the S trees were not sensitive to high water availability for the whole year, and the growth of LW was less restricted by climate changes than EW for all classes.

The study sites were situated at low elevations with strong seasonality (~90% of the 465 mm of precipitation in the growing season, and it is concentrated in July and August). In general, *Q. variabilis* primarily uptakes water from the deep soil layers (32.8%) and natural springs (43.3%) during the seasonally dry periods, and it draws up as much water as possible if there are excessive precipitation incidents [34]. Liu et al. (2019) reported that *Q. variabilis* used water mostly from deep soil layers and natural springs to ensure a continuous water supply because the water availability in the upper soil layers was insufficient [34]. Wang et al. (2017) and Peddinti et al. (2020) found that some vegetation that has developed roots can draw from deep soil water during the growing season [62,63], thereby ensuring a stable water supply. However, there may be a historical effect of short-term seasonal drought, and young trees with fewer root systems will be restricted again when seasonal drought recurs or lasts for a long time [64]. Thus, many D and CD trees obtain water from groundwater using deeper root systems if the upper soil water supply is limited, but S trees are restricted because of their undeveloped root systems. In contrast, the energy required to draw water from the deeper soil layers is higher than that from the shallow layers. The S
trees with a lower root density may not have had sufficient energy and time to absorb water from the deep soil water or natural springs during the drought seasons. In addition, the S trees were often located below the forest layer, resulting in less exposure to the atmosphere, and they may not have benefitted from better environmental conditions (i.e., light intensity, ventilation, and temperature) during the vigorous growing period compared with the other classes. Consequently, there was significant growth divergence of *Q. variabilis* in the D, CD, and S tree classes because they suffered long-term and severe seasonal droughts differently. This result is consistent with that of existing studies, which illustrated that the growth of *Q. variabilis* at this northern boundary was substantially affected by autumn water shortages [32]. In general, our findings indicate that climate change does not often restrict the growth of dominant trees, but it induces tree divergence and forest decline if warm and dry climate conditions continue beyond the adaptive capacity of tree species.

5. Conclusions

Our study site was a typical strong seasonality region, and it experiences a prolonged dry season (4–6 months). Hence, the effects of meteorological factors on the growth of planted forests in this region were a necessary concern for indication to forest managers seeking to proactively address climate-related global challenges. The novelty of our research lies in determining the impact of climatic factors on the radial growth and quality of planted forests of *Q. variabilis* in the lithoid mountainous area near Beijing, northern China. Our study revealed various responses of different crown classes to climatic changes. During drought seasons, S trees exhibit slower growth than D and CD trees under high temperatures; subsequently, they recover slowly [26]. Rising temperature under seasonal drought conditions was a critical meteorological driver that accelerated the growth decline in *Q. variabilis* plantations. Furthermore, it induced young trees to diverge significantly and early from the main canopy layers in response to continued climate change. As an extension of the planted forest density in mountainous areas, some young trees with undeveloped root systems experienced decreased water availability, low light density, and poor ventilation. Thus, restricting tree growth may also be induced by other factors, i.e., abiotic factors (light, soil, insects, and pathogens) or stand structures (tree density, total basal area, and species competition), accompanied by climatic change [20]. Indeed, the impact of climate change on radial growth and tree quality may be alleviated by adjusting and improving the stand characteristics. Our study emphasized that the resource utilization (water, light, and nutrients) of each crown class could be improved using forest thinning treatments and stand structure regulation. In this way, declining growth of planted forests under future changes in climate can be reduced and the ecosystem services that they provide maintained. To maximize the long-term forest resilience against rising aridity, we suggest the following methods based on previous studies, in addition to our findings:

1. Implementing forest thinning treatments

As a pure artificial forest ecosystem, the study area has a canopy cover of approximately 90% and a tree density of 1105 trees/ha². Consequently, excessive tree density in mountainous areas may reduce resource utilization because of enhanced species competition. Apart from climatic variables, stand structures, light density, and soil properties were also the major factors affecting the growth of planted forests. In addition, species competition for resources can gradually increase when environmental conditions improve [65]; for instance, competition among neighboring trees has gradually increased with global warming [58]. Meanwhile, tree density and total basal area reflect the crowdedness of a forest and resource efficiency levels, which can be considered competitive parameters [66]. Most studies have underscored that the growth of trees is significantly correlated with stand conditions (density and total basal area) and their interaction with the climate. For example, oak trees had higher growth in lower-density stands than in higher-density stands under drought conditions, because reducing wood density (i.e., thinning effect) mitigates species competition and increases the moisture availability for each tree class [67–69]. Therefore, reducing stand density through thinning treatments may be considered a potential adaptive
strategy for the planted forests of *Q. variabilis* in seasonal drought areas; it promotes tree vitality by increasing environmental resources (i.e., space, light, nutrients, and water), thereby increasing tree vitality [68]. Furthermore, this strategy enhances the adaptive capacity of planted forests and prevents tree mortality because of impending global warming.

2. Improving species composition

Planted forests often suffer from symmetrical competition because of monocultures or unreasonable population structures. Consequently, limited water availability during drought seasons may not satisfy the growth needs of all trees simultaneously. However, growth sensitivity to changes in resource competition stress is generally diverse among plant species. Therefore, apart from reducing stand density, forest managers may improve the resistance of forest stands to future adverse climate warming by favoring species composition. As an important silviculture strategy, diversifying tree species has many advantages, one of which is good tree growth, likely because of the complementarity effect. For example, resource partitioning or positive interactions promote resource availability and the higher growth of individuals [70]. Indeed, nutrient, light, or water availability could be more sufficient in mixture stands compared with monoculture [71,72]. Moreover, most studies indicate higher productivity for tree mixtures than monoculture [73]. An optimal proportion of the other species should mitigate the competition effect caused by complementarity. For example, mixed species could share soil water and nutrients via their different root prospecting volumes [74]. Because *Q. variabilis* grows with other species, it could prospect deeper soil layers through its root distribution, and this strategy decreases competition for water resources. In addition, if niche complementarity occurred in the above-ground component, less shade-tolerant species could occupy the upper canopy, whereas more shade-tolerant species could populate the understory. In this way, each species could use resources to increase their vitality [75]. These strategies mitigate competition for resources among different tree species and promote symbiotic relationships across community species.

In general, the planted forests of *Q. variabilis* are too dense. To avoid increased mortality and the possibility of fire becoming a natural density control factor, forests need to be thinned. Determining the most ecologically sustainable methods for maintaining ecosystem goods and services requires further investigation. Considering the increase in global warming, close-to-nature principles appear to be a suitable management option for the cultivation of more adapted forests [76,77]. However, the present study focused on a single tree species that is sensitive to climatic changes. Further research is necessary to comprehensively understand which species should be selected to improve the growth and quality of planted forests and to determine how these forests use resources during seasonal droughts in rocky mountainous areas. Studies considering several tree species will provide scientific information on silviculture and management treatments for forest plantations in rocky mountainous regions under global warming conditions.

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