Relationship between the Radial Growth of Two Dominant Coniferous Species and GPP in the Arid Region of Northwest China

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Abstract: Radial growth of trees is closely related to canopy activity. Revealing the relationship between radial growth and canopy activity is of great significance for forest protection under climate change. In this study, we built tree-ring chronologies for two tree species, spruce (Picea aspruceerata) and Chinese pine (Pinus tabuliformis), from the Helan Mountains in the arid region of northwest China. Correlation coefficients were then calculated to reveal the relationships among tree rings, two kinds of gross primary productivity (GPP) indices, and climate data. The results demonstrated that the radial growth of both spruce and Chinese pine was positively correlated with GPP from late February to early March, and moisture conditions may be the driving factor of tree growth. However, radial growth of Chinese pine was also correlated with GPP from the end of March to the end of August. This study aimed to further supplement the relationship between trunk radial growth and canopy dynamics in the arid zone of northwest China and to provide theoretical guidance for vegetation restoration and forest conservation in the arid zone of northwest China under climate change.

Keywords: Helan Mountains; tree ring chronology; GLASS GPP; EC-LUE GPP; climate factors

1. Introduction

The radial growth and canopy dynamics of trees are important processes in forest carbon sequestration and determine the carbon sink potential of forests [1]. Forests fix carbon dioxide through the canopy and distribute it to various tree organs for growth [2], among which the trunk is the primary site of carbon sequestration. Therefore, trunk growth is partially influenced by tree canopy activity. The study of the relationship between tree trunks and the canopy is to reveal the physiological mechanism of tree carbon sequestration and provide a theoretical basis for increasing forest carbon sequestration. Recent studies on the relationship between radial tree growth and canopy dynamics have mainly centered on the relationship between tree rings and canopy phenology and between tree rings and the normalized difference vegetation index (NDVI) [3–5]. Several studies have discovered that there is a significant correlation between the radial growth of several coniferous species and NDVI during the tree growing season. Studies in the Bayinbuluke region of Xinjiang have found a significant positive correlation between radial growth of spruce and NDVI from June to August [6]. In the source area of the Yangtze River, studies have found the most significant correlation between radial growth of trees and NDVI in July and August [7]. Studies in the Qilian Mountains have found high consistency between spruce ring width index and NDVI in this region [8]. Similar findings were reported in the southwestern United States; studies have found that the radial growth of Pinus edulis, Pinus Ponderosa and Pseudotsuga menziesii is most closely correlated with NDVI from June to August in the...
southwestern United States [9]. Furthermore, studies in the northern subtropical region have found that the ring width of *Pinus massoniana* is highly consistent with NDVI in September [10]. However, NDVI is calculated based on the absorption and reflection of light at different wavelengths by chlorophyll in vegetation, which characterizes the surface vegetation cover [11] and does not directly respond to the activity of the canopy, making NDVI uncertain in response to conifers and bringing uncertainty to the correlation results.

Compared to NDVI, gross primary productivity (GPP) is the amount of organic carbon fixed by photosynthesis in green plants per unit of time [12], which is an important indicator of the photosynthetic capacity of vegetation and is more representative of vegetation canopy activity [13]. Thus, studying the relationship between tree rings and GPP can directly reveal the relationship between radial growth and crown carbon sequestration. With the development of remote sensing technology, GPP inversion has made a lot of progress. In the last few years, some researchers have used several methods to calculate GPP based on remote sensing data and meteorological data from flux sites [14] and have obtained several GPP products. For example, the revised EC-LUE model is generated by integrating the regulation of several major environmental variables such as atmospheric CO$_2$ concentration, radiation components (i.e., direct and diffuse radiation), and atmospheric water vapor pressure difference (VPD). The revised EC-LUE can better simulate the spatial, seasonal, and interannual changes of global GPP. Especially at the site level and global scale, it has unique advantages in reproducing the interannual changes of GPP. Another GPP product, the GLASS GPP collection, currently consists of eight internationally and widely used light energy utilization models: CASA, CFix, CFlux, EC-LUE, MODIS, VPM, VPRM, and Two-leaf. The algorithm development and verification use remote sensing and meteorological data simultaneously based on the global vortex-related flux site data. The number of sites is 155, including 9 types of terrestrial ecosystems: evergreen broad-leaved forest, evergreen coniferous forest, deciduous broad-leaved forest, mixed forest, temperate grassland, tropical savanna, shrubs, farmland, and tundra. In addition to GPP estimates provided by various methods, these two remote sensing-based GPP products provide a high time resolution of 8 days. Therefore, analyzing the relationship between tree-ring and 8-day GPP can more intuitively and accurately reflect the relationship between radial tree growth and canopy activity.

The Helan Mountains are the demarcation line between arid and semi-arid areas in northwest China, which makes the vegetation in the region very sensitive to climate change [15]. The forest in this region is an important barrier against the advancement of the northwest desert; therefore, studying forest growth strategies is highly significant. Previous studies have focused on the relationship between secondary growth of tree rings and climate, whereas the relationship between primary and secondary growth of the forest itself has rarely been studied. Therefore, we aimed to study the relationship between radial growth and canopy dynamics (tree rings and GPP) of the dominant tree species in the Helan Mountains, spruce (*Picea aspruceerata*) and Chinese pine (*Pinus tabuliformis*), at higher temporal scales to provide a basis for an in-depth understanding of the coordination of various organs in the forest in the dry zone of northwest China and provide some theoretical guidance for vegetation restoration and forest conservation under climate change.

2. Material and Methods

2.1. Study Region

The Helan Mountains (38°19′–39°22′ N, 105°49′–106°41′ E) (Figure 1) are located at the boundary between Ningxia Hui Autonomous Region and Inner Mongolia Autonomous Region, with an altitude of 2000–3000 m. The Helan Mountains, a narrow north–south arc with a total length of >200 km and a width of approximately 30 km from east to west, are an important geographical boundary in northwest China [15,16] and are highly sensitive to climate change. The high terrain of the Helan Mountains has unique climate characteristics, including cold winters, cool summers, and relative high precipitation [17,18]. The Helan Mountains are stony and infertile; therefore, the vegetation type is simple, and the coverage
is low. Two coniferous species, spruce and Chinese pine, were the dominant species, followed by poplar (*Populus davidiana*), *Ulmus macrocarpa* (*Ulmus macrocarpa*), birch (*Betula platyphylla*), and various wild fruit trees and shrubs [19,20].

**Figure 1.** Elevation map of Ningxia Hui Autonomous Region.

### 2.2. Tree-Ring Data

Spruce and Chinese pine forests with no significant human influence were selected (located on N105.901° E38.775° and N105.911° E38.745°, respectively) as target tree species. An increment borer with an inner diameter of 5.15 mm was used to drill the tree-ring cores from the vertical slope direction, and two cores were drilled from each tree. After the cores were naturally dried, they were fixed in the sample wooden slot with manual white glue. After the latex dried, the sample was ground step by step with sandpaper of different mesh sizes (from 180 mesh to 1000 mesh) until the xylem cells were clearly visible under the microscope. Visual cross dating was carried out under the microscope. Then LINTAB 6 with TSAP software was used to measure tree-ring width with an accuracy of 0.01 mm. The initial dating results were cross-checked using COFECHA software [21], and any errors in dating were corrected. Samples with severe fractures that made it difficult to cross-date were removed, and, finally, 55 cores from 31 spruce trees and 31 cores from 19 Chinese pine trees were used for subsequent analysis.

After obtaining accurate tree-ring data, ARSTAN software was employed to build species-specific chronologies [22]. Smooth spline with a 50% frequency cutoff equal to 32 years was employed to detrend the non-climatic signals. Then, the detrended series was synthesized using the Robust Bi-weight averaging method to develop three types of chronologies: standard chronologies (STD), residual chronologies (RES), and ARSTAN chronologies (ARS). Here we used the residual chronologies for subsequent analyses. A common period analysis was conducted from 1982–2018, and the signal-to-noise ratio (SNR), expressed population signal (EPS), and variance in the first eigenvector (PC1) were calculated to evaluate the quality of the chronologies. Finally, the chronologies were truncated using the 0.85 threshold of subsample signal strength (SSS) [23].

### 2.3. GPP Data

Given that the inversion of GPP is based on different methods, we chose two different GPP products for analysis with tree rings to make the results more reliable. GLASS GPP
data from Earth System Science Data (https://doi.org/10.6084/m9.figshare.8942336.v3, accessed on 1 June 2022) with a spatial resolution of 0.05° and a temporal resolution of 8 days from 1982–2018 were downloaded. This was based on MODIS remote sensing data and meteorological data from flux sites, using a Bayesian multi-algorithm integration approach, integrating the following eight light energy utilization models that are currently widely used internationally: CASA, CFix, CFlux, EC-LUE, MODIS, VPM, VPRM, and Two-leaf [14].

EC-LUE GPP comes from the National Basic Condition Platform for Science and Technology; the National Earth System Science Data Sharing Service Platform (http://www.geodata.cn, accessed on 2 June 2022). This product with a spatial resolution of 0.05° and a temporal resolution of 8 days from 1982 to 2018 is an EC-LUE model modified by Wenping Yuan et al., which integrates the effects of atmospheric CO₂ concentration, solar radiation, and atmospheric vapor pressure deficit (VPD) based on the original EC-LUE model driven solely by four variables: normalized difference vegetation index (NDVI), photosynthetic effective radiation (PAR), temperature, and the Bowen ratio of sensible and latent heat fluxes. The modified EC-LUE model can effectively simulate the spatial, seasonal, and interannual changes of global GPP [24,25].

The downloaded GPP data were processed in ArcMap using the crop and value extraction to point tools; the extracted GPP data were also detrended in R with package “stat” to obtain the GPP data corresponding to the tree-ring sampling sites. In total, for each GPP product, 46 8-day GPP values per year were calculated, and the time span was from 1982 to 2018 (see Figures S1 and S2). In addition, considering the asynchronism between tree photosynthesis and trunk growth, we also calculated the cumulative GPP values at different time scales (1–92 8-day, a total of 92 scales) to reveal the relationships between radial growth and canopy growth [26]. For example, when calculating the three cumulative 8-day scales of the 21st 8-day GPP, we added the 21st 8-day and two 8-days from 19–20. Finally, we obtained the 1–92 scales of the 1st to 46th 8-days at a 2-year scale (from the previous year to current growth year), which counted for 4232 time series (92 × 46).

2.4. Climate Data

We also calculated the correlation coefficients between meteorological data and tree-ring chronologies to further reveal the factors driving radial growth dynamics. Meteorological datasets were obtained from the meteorological stations in Yinchuan, Ningxia, from 1982 to 2018 from the China International Meteorological Center (http://cdc.nmic.cn/home.do, accessed on 12 July 2022), and the meteorological factors were selected as precipitation (Pre), monthly mean temperature (Mean-T), monthly maximum temperature (Max-T), monthly minimum temperature (Min-T), relative humidity (RH), and sunshine duration (SD). In addition, the standardized precipitation evapotranspiration index (SPEI) data were also used, which was calculated based on the meteorological data obtained from the China International Meteorological Center using the ETaCalculator software on the official website of FAO to calculate ETo (Penman–Monteith formula) and then based on ETo and precipitation data using Climate Data Toolbox (CDT) in MATLAB to obtain the SPEI data [27].

The climate conditions are shown in Figure 2. During the period 1982–2018, the multi-year monthly average precipitation was 193.2 mm, which was mainly focused on the period from July–August, accounting for 43.70% of the annual precipitation; the highest and lowest monthly average temperature occurred in July at 24.10 °C and January at −7.11 °C, respectively; the highest and lowest SPEI was 1.4735 in June and 0.2422 in December, respectively; the highest and lowest monthly average relative humidity was 64.86% in July and 38.36% in April, respectively; and the highest and lowest monthly average sunshine duration was 283.24 h in May and 181.30 h in December, respectively.
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Figure 2. Multi-year monthly climate data trends for meteorological stations in Yinchuan, 1982–2018. (Max-T, mean monthly maximum temperature; Min-T, mean monthly minimum temperature; Mean-T, mean monthly mean temperature; SPEI, mean monthly standardized precipitation evapotranspiration index; RH, mean monthly relative humidity; SD, mean monthly sunshine duration; Pre, mean monthly precipitation).

2.5. Data Processing

The two GPP products provide continuous data since 1982. Therefore, this study analyzed the tree ring–GPP relationship since 1982. Correlations between 8-day GPP data and 2-year cumulative scale GPP data and tree-ring data from to 1982–2018 were analyzed in R using the “corrplot” package [28]; the “treeclim” package [29] was used to analyze the correlations between meteorological and tree-ring data from 1982–2018, with months from January of the previous year to December of the current year being selected.

3. Results

3.1. Characteristics of Tree-Ring Growth

The characteristics of the two residual chronologies are listed in Table 1. The average sensitivity of the chronologies was greater than 0.4, indicating that tree growth is influenced by environmental changes [30–32]. The high values of SNR, EPS, and PC1 indicate that our chronologies were sufficiently robust for analysis. The two chronologies are shown in Figure 3. The expressed population signa (EPS) of spruce has been >0.85 since 1889 and that of Chinese pine has been >0.85 since 1916. Overall, even the sample sizes of the two species were different due to the distribution area. The statistical diagnosis of the two chronologies from 1982–2018 reached the threshold and was suitable for conducting further investigations.

3.2. Response of Tree Rings to GPP

Correlation coefficients between spruce chronology and GLASS GPP and between spruce chronology and EC-LUE GPP were shown in Figure 4 and Figure S3. The results for GLASS GPP and EC-LUE GPP were basically the same. The GPP and tree-ring analysis based on both algorithms obtained the same results, indicating that the relationship between radial growth and canopy dynamics is reliable. Spruce radial growth was significantly positively correlated with the seventh and the eighth 8-day GPP on a one 8-day scale (for GLASS GPP, r was 0.398 and 0.417, p < 0.05; for EC-LUE GPP, r was 0.400 and 0.417,
When considering the lag effect, significant positive correlations were detected on the 2–12 cumulative 8-day scale of the seventh–eighth 8-day (for cumulative GLASS GPP, $r$ ranged from 0.320 to 0.445, $p < 0.05$; for cumulative EC-LUE GPP, $r$ ranged from 0.326 to 0.589, $p < 0.05$) (Figure 4a and S3a). This resulted in a significant positive correlation between GPP and spruce radial growth primarily in late February to early March; in a 2-year cumulative scale, spruce radial growth was significantly and positively correlated with cumulative GPP from November of the previous year to early March of the current year.

### Table 1. Characteristic of the standardized tree-ring width residual chronology.

<table>
<thead>
<tr>
<th></th>
<th>Tree-Ring Width (Mean ± Standard Deviation) (mm)</th>
<th>Correlation Coefficients between Cores</th>
<th>Standard Deviation</th>
<th>Mean Sensitivity</th>
<th>Expressed Population Signal</th>
<th>Variance in First Eigenvector (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>spruce</td>
<td>0.98 ± 0.72</td>
<td>0.718</td>
<td>0.426</td>
<td>0.432</td>
<td>0.993</td>
<td>73.0%</td>
</tr>
<tr>
<td>Chinese pine</td>
<td>1.09 ± 0.84</td>
<td>0.474</td>
<td>0.406</td>
<td>0.465</td>
<td>0.965</td>
<td>59.6%</td>
</tr>
</tbody>
</table>

The relationships between the Chinese pine chronology and the two GPP indices are shown in Figures 5 and S4. They also reveal similar results. Significant and positive correlations were observed with the 1–12 cumulative 8-day scales of the seventh–eighth 8-day (for GLASS GPP, $r$ ranged from 0.348 to 0.405, $p < 0.05$; for EC-LUE GPP, $r$ ranged from 0.326 to 0.589, $p < 0.05$) (Figures 5a and S4a), which is similar to the results between spruce and GPP. However, the Chinese pine was also positively correlated with the 1–10 cumulative 8-day scales of the 17th–30th GPP (for cumulative GLASS GPP, $r$ ranged from 0.322 to 0.419, $p < 0.05$; for cumulative EC-LUE GPP, $r$ ranged from 0.320 to 0.407, $p < 0.05$) (Figures 5b and S4b) from late March to the end of August.
3.3. Response of Tree Rings to Climate

The radial growth of spruce was the most significantly correlated with climatic conditions in March of the current year and was significantly and positively correlated with precipitation \( (r = 0.579) \), relative humidity \( (r = 0.426) \), and SPEI \( (r = 0.501) \), whereas it was significantly negatively correlated with sunshine duration \( (r = -0.542) \). In addition, it also had a significant correlation with the climatic conditions in October of the previous year, and May and September of the current year, among which it had a significant and positive correlation with the maximum temperature \( (r = 0.458) \) and sunshine duration \( (r = 0.378) \) in October of the previous year, SPEI \( (r = 0.397) \), and precipitation \( (r = 0.424) \) in May of the current year and the maximum temperature \( (r = 0.433) \) in September of the current year. There was a significant and negative correlation between the SPEI \( (r = -0.343) \) in October of the previous year and the SPEI \( (r = -0.381) \) and precipitation \( (r = -0.348) \) in September of the current year (Figure 6).

The radial growth of the Chinese pine was the most significantly correlated with the climatic conditions in March and May of the current year and was positively correlated with precipitation \( (r = 0.579 \text{ for March}; r = 0.542 \text{ for May}) \), relative humidity \( (r = 0.454 \text{ for March}; r = 0.369 \text{ for May}) \), and SPEI \( (r = 0.4489 \text{ for March}; r = 0.53 \text{ for May}) \) but negatively correlated with sunshine duration \( (r = -0.416) \) and maximum temperature \( (r = -0.335) \) in May. In addition, it was significantly correlated with the climate in June and October of the previous year, among which it was significantly and positively correlated with the maximum temperature and sunshine duration in June and October of the previous year and the maximum temperature \( (r = 0.378) \) in October of the previous year. There was a significant and negative correlation between the SPEI \( (r = -0.462) \) and relative humidity \( (r = -0.361) \) in June and SPEI \( (r = -0.352) \) in October (Figure 7).
which ultimately facilitates the division of cambium cells and leads to the widening of (Max-T, mean monthly maximum temperature; Min-T, mean monthly minimum temperature; Mean-T, mean monthly mean temperature; SPEI, mean monthly standardized precipitation evapotranspiration index; RH, mean monthly relative humidity; SD, mean monthly sunshine duration; Pre, mean monthly precipitation) (*, ** and *** indicate significance at 0.1, 0.05 and 0.01 level, respectively).

found a significant correlation between radial growth and water availability [49].

between radial growth of trees and moisture conditions [47,48]. Studies in Spain have found a significant correlation between radial growth of spruce and water in low altitude areas of the middle Qilian Mountains [45]. Studies in the Tianshan Mountains [43]. Du et al., 2022 found a significant correlation between radial growth of spruce and water [6]. Qin et al., 2021 found a significant correlation between radial growth of spruce and water in the Qilian Mountains [44]. Wang et al., 2020 found a significant correlation between radial growth and water [4].

activity, thus promoting photosynthesis and increasing the accumulation of nutrients, this period (late February to early March) is key to tree growth, which is consistent with previous research on GPP and tree rings have rarely been reported, which cannot support our findings. However, some studies have been conducted on tree rings and NDVI around our study area. For example, Zhang et al., 2021 found a high correlation between radial growth of spruce in Bayinbruck and NDVI from June to August [6]. In Qinling, Shaanxi Province, Ran et al., 2021 found a high correlation between radial growth of Chinese pine and NDVI from May to July [33]. In the Huanglong Mountains, Wang et al., 2017 found a high correlation between radial growth of Chinese pine and NDVI from June to July [34]. Li et al., 2020 found a high correlation between radial growth of Chinese pine in the Helan Mountains and NDVI from May to July [35]. Compared with our results, it can be found that there is a significant correlation between tree rings and GPP in the early growing seasons and even before the growing seasons, while the significant correlation between tree rings and NDVI were found in the mid-growing season (May to August). This may be due to the allocation strategy of organic matter produced by the canopy among different organs. This also indicates that, compared to studying the relationship between tree rings and NDVI, revealing the relationship between tree rings and GPP directly has more physiological significance and can lead to some new conclusions.

The relationship between tree rings and climate also shows that water supply during this period (late February to early March) is key to tree growth, which is consistent with the results of tree-ring research conducted around areas [36–40]. This is because, in arid areas, adequate water supply in the early growth season indicates that roots can access water more easily which can ensure more water use in the canopy and increase canopy activity, thus promoting photosynthesis and increasing the accumulation of nutrients, which ultimately facilitates the division of cambium cells and leads to the widening of tree rings [41,42]. This phenomenon has been widely reported in arid or semi-arid areas. Studies in the Bayinbuluke region of Xinjiang have found a significant correlation between radial growth of spruce and water [6]. Qin et al., 2021 found a significant correlation between radial growth of spruce and water in the Tianshan Mountains [43]. Du et al., 2022 found a significant correlation between radial growth of spruce and water in the Qilian Mountains [44]. Wang et al., 2020 found a significant correlation between radial growth of spruce and water in low altitude areas of the middle Qilian Mountains [45]. Studies in Arizona, USA, have found a significant correlation between radial growth of ponderosa pine and water [46]. Studies in the Mediterranean region have found a significant correlation between radial growth of trees and moisture conditions [47,48]. Studies in Spain have found a significant correlation between radial growth and water availability [49].
4.2. Difference between Spruce and Chinese Pine

Spruce was mainly related to canopy activity from November to March of the previous year [50,51]; however, the correlation was not significant thereafter. The relationship with climate was mainly related to March moisture, followed by May moisture, but the relationship with May moisture was less significant than that with March moisture. This is similar to the results of the research on microcores conducted in Canada. Huang et al., 2014 studied balsam fir (Abies balsamea) and black spruce (Picea mariana) in Canada and observed that radial growth could be correlated with cambium activity, bud phenology, and growth phenology of branches and needles, indicating the importance of primary growth in xylem formation in spruce [52]. A possible reason for this is that the elevation of spruce in the Helan Mountains is higher, and the growing season is shorter. Therefore, the environmental factors during the early growing season determine the radial growth of spruce throughout the growing season.

The Chinese pine is closely related to canopy activity throughout the growing season, from March to August. This was also confirmed by the tree ring–climate relationship. These results were similar to those of the Chinese pine studied in the northwest [36,53]. The relevant reasons have not yet been notably reported. We speculate that the possible reasons for this are that the Chinese pine has a lower distribution altitude, better hydrothermal conditions than spruce, and a longer growing season [54]. Therefore, better moisture conditions in the early growing season maintain high growth in the early growing season, and it still has a certain growth ability in the late growing season, which is highly dependent on canopy activity. Further analysis of the physiological characteristics of Chinese pine is required to confirm this hypothesis.

5. Conclusions

To reveal the relationships between radial growth and canopy activity, we analyzed the relationship between two GPP indices and tree-ring chronologies of spruce and Chinese pine. The results showed that the radial growth of spruce was significantly related to the GPP before the growth season (November of the previous year to current March), while the radial growth of Chinese pine was significantly related to the GPP during the growth season (from March to August). Our results indicated that there are certain differences in research on GPP and NDVI, and research related to GPP has more physiological significance. In addition, there are differences in the results between spruce and Chinese pine, which may be related to differences in organic matter allocation strategies or differences in habits (spruce has shallow roots, prefers shade and Chinese pine has deep roots and prefers sunlight). This requires further research in the future. Our findings will help to conduct forest management to face climate change.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f14071336/s1, Figure S1. Interannual trend distribution of GLASS GPP ((a): spruce (b): Chinese pine). Figure S2. Interannual trend distribution of EC-LUE GPP ((a): spruce (b): Chinese pine). Figure S3. Correlation between the chronology of residuals of spruce tree-ring and EC-LUE GPP ((a): 8-days scale (b): cumulative scale). The dotted line indicates the significant level of 0.95. Figure S4. Correlation between the chronology of residuals of Chinese pine tree-ring and EC-LUE GPP ((a): 8-days scale (b): cumulative scale). The dotted line indicates the significant level of 0.95.

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Data Availability Statement: Data is unavailable due to privacy.

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