

Article

Growth Response of *Pinus tabuliformis* and *Abies fargesii* to Climate Factors in Southern Slope of Central Qinling Mountains of China

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Abstract: The response of trees to climate is crucial for the health assessment and protection of forests in alpine regions. Based on samples of *Pinus tabuliformis* and *Abies fargesii*, two typical evergreen coniferous species with distinct elevation differences in the vertical vegetation zones of the Qinling Mountains, we have developed two tree-ring width chronologies for the southern slope of the central Qinling Mountains in central China. The correlation analysis results showed that the radial growth of *P. tabuliformis* and *A. fargesii* responded to different climatic factors. Water stress caused by temperature in May of the current year was the main limiting factor for radial growth of *P. tabuliformis*, while precipitation in September of the previous year and the current year had a negative impact on *A. fargesii*, with lag effects of temperature and precipitation during the previous growing season. Spatial correlation and comparative analysis indicated that the *P. tabuliformis* chronology responded to extreme dry and wet events on a regional scale. Interannual and multidecadal periodic signals recorded by tree rings suggested that the hydrological and climatic changes on the southern slope of the central Qinling Mountains were teleconnected with the Pacific and Atlantic Oceans, including El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and North Atlantic Oscillation (NAO). Our results provide new evidence for a hydroclimatic response study inferred from tree rings on the southern slope of the central Qinling Mountains.

Keywords: tree rings; central Qinling mountains; East Asian summer monsoon



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1. Introduction

The Qinling Mountains are located in the central part of China, serving as the geographical dividing line between the north and south of China, as well as the boundary between the subtropical and warm temperate zones and the humid and semi-humid climate zones [1,2]; they are highly sensitive to climate change [3,4]. Amidst the background of global warming in the 21st century, climate changes and their potential impacts on the Qinling Mountains and surrounding areas have attracted much attention [5,6]. As a primary

research method for global change, tree rings play a significant role in historical climate change due to their precise high-resolution dating, extensive geographical distribution, and sampling collection [7]. Studies of climate change in the Qinling Mountains using tree rings have yielded valuable results. For instance, research results from the eastern part of the Qinling Mountains, Mount Hua, indicate that temperature in April and precipitation from April to July are the main limiting factors for the radial growth of *Pinus armandii* and are closely related to the temperature in June [8]. Then, the precipitation from April to July for Mount Hua was reconstructed, and the results were comparatively analyzed [9,10]. Studies on the differences in the response of tree growth of *P. tabuliformis* to climatic factors over the Qinling Mountains show that the radial growth of trees on the north slope record temperature changes during the early summer growing season, i.e., from May to July, while trees on the south slope significantly respond to temperature changes in the winter half-year, i.e., from the previous September to the current April [11]. Previous studies have found differences in the radial growth of *A. fargesii* at different altitudes on the southern and northern slopes of the Qinling Mountains [12,13]. Early spring to summer temperatures are the main limiting factors for the radial growth of *A. fargesii* at middle and low altitudes, while summer precipitation affects the growth of trees at high altitudes [12]. The responses of *A. fargesii* to climatic factors are also related to the ages of trees [14].

Therefore, the history of the average temperature variability from January to July in the central watershed area of the Qinling Mountains over the past 200 years was reconstructed [15]. The responses of trees growing at high altitudes in the Qinling Mountains to temperature and precipitation could cover the Guanzhong area of Shaanxi Province and have the ability to represent climate changes over a larger area [16,17]. Based on tree-ring width and density indicators, the streamflow of the Weihe River on the north slope of the Qinling Mountains over the past 400 years was reconstructed, revealing the interannual and interdecadal hydrological variability and its teleconnections with remote oceans such as the Pacific, Indian, and Atlantic Oceans [18,19]. The above studies indicate that tree-ring data are an effective way to study and restore the environmental evolution and climate change in the Qinling Mountains. However, the Qinling Mountains span a large area from east to west, and the terrain from north to south is complex and diverse [20,21]. Especially in the central part of the Qinling Mountains, where the highest peak of Mount Taibai is located, there are obviously local climate conditions [22].

P. tabuliformis [23] and *A. fargesii* [24,25] are dominant tree species in the Qinling region, playing an important role in regional water conservation and biodiversity protection. They are also the main tree species for dendrochronological research in the Qinling region [11–14,18,19,23].

The patterns of tree radial growth to climatic factors in different tree species and different site environments are of great significance for the construction of the Qinling National Park and the management and protection of forests [26,27].

The objectives of this work are (1) to establish the tree-ring width chronologies of *P. tabulaeformis* and *A. fargesii* on the southern slope of the central Qinling Mountains; (2) to determine the response characteristics of the radial growth of the two tree species to climatic factors; and (3) to explore the regional representativeness of the new chronologies and possible atmospheric teleconnections. Our results could provide new evidence for the comprehensive multi-temporal and multi-spatial scale study of tree rings over the entire Qinling Mountains.

2. Materials and Methods

2.1. Tree-Ring Data

Sampling sites are located on the southern slope of the central Qinling Mountains at Huangbaiyuan (HBV, 107°40' E, 33°48' N, 1602 m above sea level) and Nantianmen on the southern slope of Taibai Mountain (NTM, 107°46'47.59'' E, 33°54'55.88'' N, 3063 m above sea level) (Figure 1). The former is *P. tabuliformis*, while the latter is *A. fargesii*. Both tree-ring sampling sites are located on flat slopes near cliffs and are pure forests. Tree-ring samples were collected using increment borers, and they were treated with fixation, air drying, and sandpaper polishing in the laboratory [28]. The Lintab 6 tree-ring station was used for measuring ring widths with a precision of 0.01 mm (www.rinntech.de) (Rinntech-Metriwerk GmbH & Co. KG, Heidelberg, Germany). The original data were cross-dated using COFECHA (Version 6.06) [29], and the ARSTAN (Arstan_41xp software program) [30] program was utilized to standardize ring-width series, thereby establishing a tree-ring chronology. This study employed negative exponential and linear fitting methods to remove growth trends caused by the genetic factors of the trees themselves and non-climatic growth trends caused by inter-tree competition. Each tree-ring series was divided by the dimensionless index obtained from the fitted curve, and a chronology was established using the biweight robust mean method; ultimately, two types of chronologies were established, i.e., standard chronology (STD) and residual chronology (RES) [30]. The HBV chronology includes 29 cores from 28 trees, while the NTM chronology includes 14 cores from 11 trees. The STD chronology retains a greater amount of low-frequency climatic signals after removing the growth trend-related tree ages, whereas the RES chronology retains a higher proportion of high-frequency signals after removing local environment impacts near trees and lagged effects from previous periods on current growth [30]. Studies have indicated that comparative analysis of multiple chronologies in semi-humid regions can provide more information on climate-growth responses [31]. The STD and RES chronologies were used for climate growth response analysis, and the tree-ring width index curves and sample depth are shown in Figure 2.

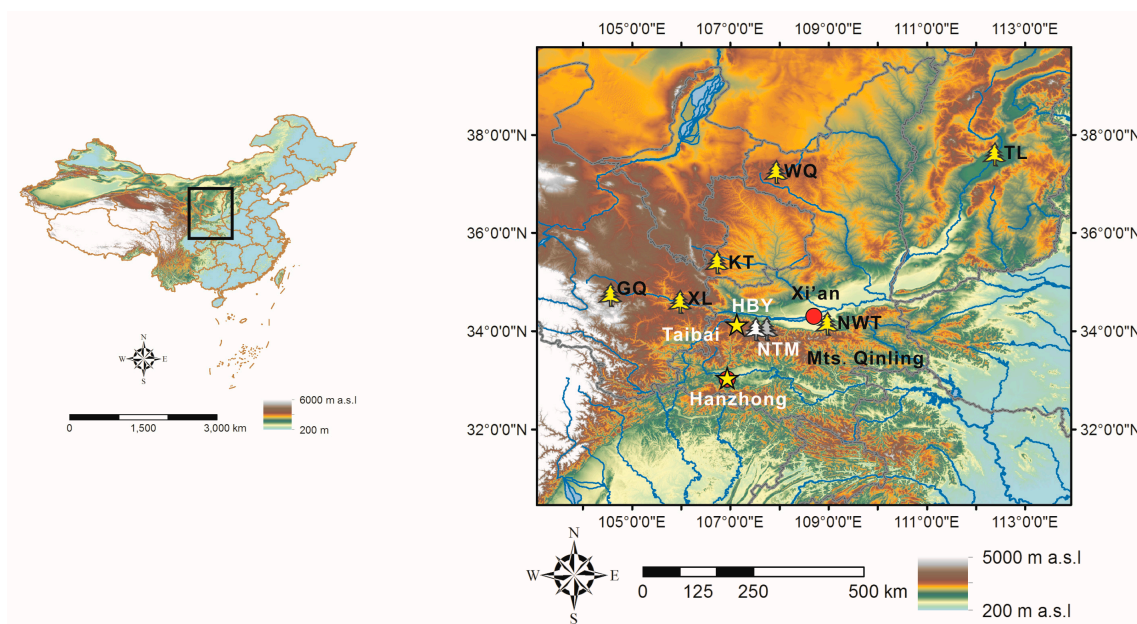


Figure 1. Tree-ring sites (HBV: white tree; NTM: grey tree used in this study, yellow tree for comparison and discussion), stations of meteorology (yellow star), and drought and flood index (red cycle).

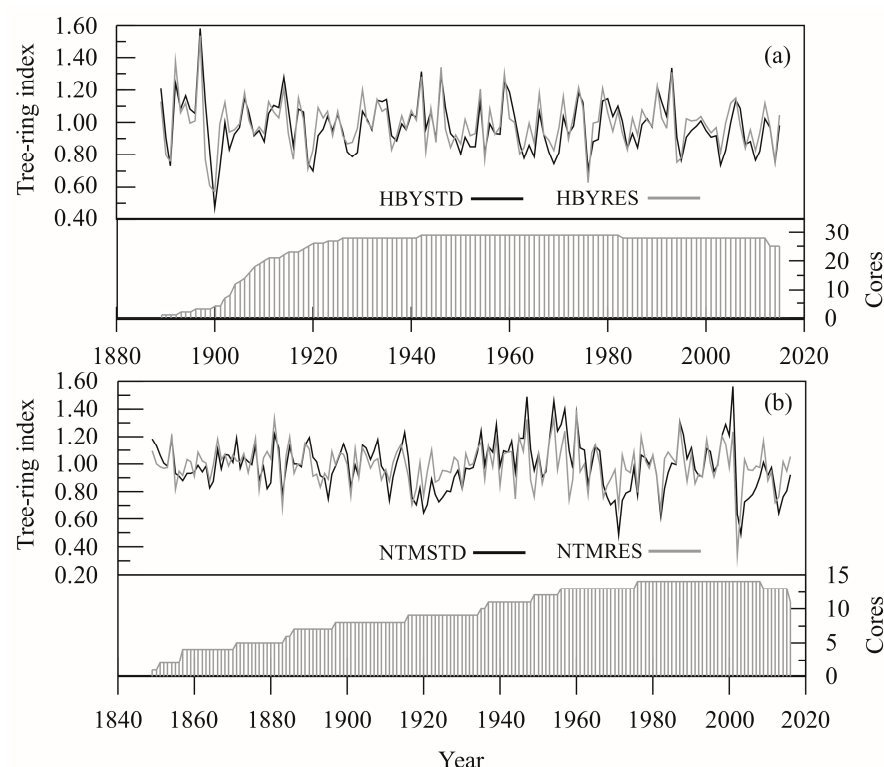


Figure 2. Tree-ring width standard chronology and residual chronology of (a) Huangbaiyuan (HBY) and (b) Nantianmen (NTM) and sample depth.

The HBY chronology spans 127 years, covering the period from 1889 to 2015, while the NTM chronology is 168 years, covering the interval from 1849 to 2016. The ranges of mean values and mean sensitivities of the chronologies are 0.976–0.993 and 0.133–0.180, respectively (Table 1). The values of the signal-to-noise ratio (SNR), the expressed population signal (EPS), and the variance of the first principal component are all lower in the standard chronology than in the residual chronology (Table 1) [30]. The EPS value 0.744 of HBYSTD is relatively low, but there is a significant correlation ($r = 0.84$, $p < 0.01$) between the HBYSTD and HBYRES chronologies (with an EPS 0.896 for HBYRES). Especially during the period from 1902 to 2014, both HBYSTD and HBYRES show a highly consistent pattern of variation (Figure 2). The subsequent correlation analysis is also based on a sufficient sample size. Therefore, to ensure the reliability of the analysis, a minimum of 5 cores was selected as the threshold [32], resulting in effective chronologies for HBY from 1902 to 2015 and for NTM from 1871 to 2016.

Table 1. Statistical characteristics of the Huangbaiyuan (HBY) and Nantianmen (NTM) chronologies.

Statistics	Tree-Ring Width Chronology			
	HBYSTD	HBYRES	NTMSTD	NTMRES
Mean value	0.976	0.991	0.985	0.993
Standard deviation (SD)	0.157	0.154	0.179	0.145
Mean sensitivity (MS)	0.147	0.180	0.133	0.170
Serial correlation	0.323	−0.142	0.548	−0.061
Signal-to-noise ratio (SNR)	2.899	8.621	5.707	8.127
Expressed population signal (EPS)	0.744	0.896	0.851	0.890
Variance of the first eigenvector (%)	22.500	30.700	47.400	51.800
Length of chronology	127	127	168	168

2.2. Meteorological Data and Statistical Methods

Meteorological data were obtained from the China Meteorological Science Data Sharing Service Network (<http://data.cma.cn/site/index.html>) (accessed on 1 August 2024). Monthly data from the Taibai Meteorological Station (107°19' E, 34°02' N, 1543 m above sea level) and the Hanzhong Meteorological Station (107°02' E, 33°04' N, 509.5 m above sea level), which are closer to the sampling sites, were selected to represent the climatic characteristics of the southern slope of the central Qinling Mountains, covering the period from 1958 to 2011. Monthly average temperature and precipitation distributions show that the climatic elements of the southern slope of the central Qinling Mountains have similar characteristics of heat and rain in summer (June–August) and cold and dry conditions in winter (December, January–February). July has the highest temperature and precipitation throughout the year, and high temperatures and precipitation concentrate from July to September (Figure 3a). It should be noted that there is a significant difference in elevation between the Hanzhong meteorological station and the NTM site, which may influence the response results between tree rings at NTM and climatic factors. Although similar elevation differences in the climatic response of tree radial growth have been reported on Mountain Taibai [33], that is, by analyzing the temperature and precipitation at the Taibai meteorological station with *Larix chinensis* at an elevation of 3400–3500 at the top of the Qinling Mountains, the warmth index over the past 300 years have been reconstructed. In this study, we used the average gridded climate data from CRU for the growth climate response analysis for NTM chronology, with a grid range of 107° E–108° E, 33° N–34° N; a resolution of $0.5^{\circ} \times 0.5^{\circ}$; and a period from 1958 to 2011. The selected area covered two meteorological stations and tree-ring sampling sites, including monthly average temperature, maximum temperature, minimum temperature, and monthly precipitation. The characteristics of the gridded climate data changes were almost completely consistent with the meteorological stations (Figure 3b). A previous study on the climate response of *A. fargesii* near the Qinling South Slope in the study area [14] indicated that CRU data can be used for NTM tree ring analysis. The drought and flood index (DFI) determined by the historical literature reflects the characteristics of hydrological changes in the region under the influence of the East Asian summer monsoon in eastern China [34]. This study selects the drought and flood index from the Xi'an station on the northern slope of the Qinling Mountains and the Hanzhong station on the southern slope for comparative analysis of the dry and wet conditions in extreme years of tree-ring width index. Pearson correlation analysis is used to identify the correlation between climatic factors and tree-ring width index [18]. Since climatic factors from the previous year could have a lagged effect on the growth of trees in the current year, the climate–growth response analysis is conducted for the period from May of the previous year to October of the current year, covering the period from 1958 to 2011. To explore the regional climate change reflected by the current tree rings on the southern slope of the Qinling Mountains, spatial correlation analysis is performed between the HBY chronology and grid data (<http://climexp.knmi.nl>), including temperature [35], precipitation [35], and the Standardized Precipitation Evapotranspiration Index (SPEI) [36], covering the period from 1902 to 2015. The main oscillation signals in the tree-ring chronology are extracted using the multi-taper method (MTM) [37].

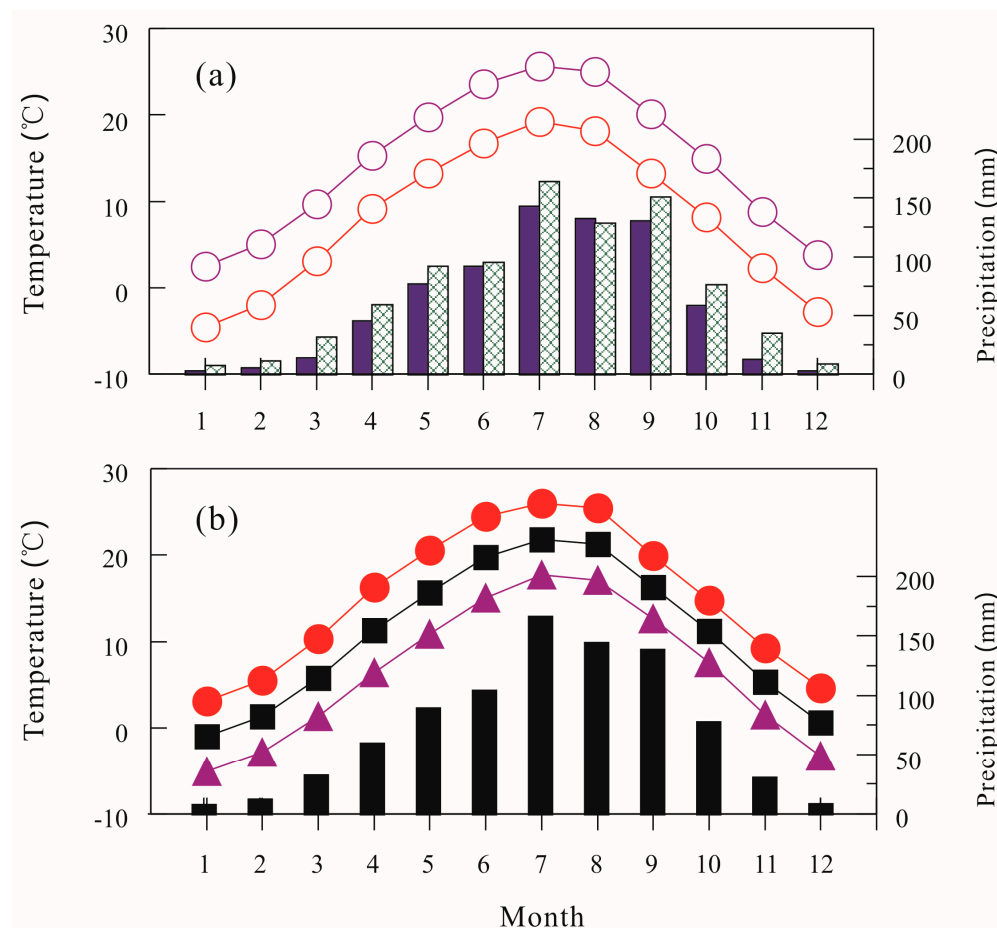


Figure 3. (a) Monthly mean temperature (circles) and precipitation (bars) from Taibai (red circle, blue bar) and Hanzhong (purple circle, green cross bar) meteorological station (1958–2011). (b) The same for CRU grid data (red dot: the max temperature; black square: the average temperature; purple triangle: the minimum temperature; black bar: monthly precipitation).

3. Results

The radial growth responses of HBY and NTM to climatic factors are shown in Tables 2 and 3. Specifically, HBYSTD was significantly negatively correlated with the average temperature in May at the Hanzhong and Taibai stations, with correlation coefficients of -0.348 ($p < 0.01$) and -0.404 ($p < 0.01$), respectively. NTMSTD was negatively correlated with the mean maximum temperature in June of the previous year (-0.269 , $p < 0.05$) while positively correlated with maximum temperatures in September (0.368 , $p < 0.01$) and December (0.293 , $p < 0.05$) of the previous year and current September (0.275 , $p < 0.05$), as well as the mean minimum temperature in the current June (0.297 , $p < 0.05$). Significant negative correlations existed between NTMSTD and precipitation in September of the previous and current year (-0.375 , $p < 0.01$; -0.288 , $p < 0.05$), respectively. NTMRES was negatively correlated with the mean temperature (-0.290 , $p < 0.05$) and maximum temperature in July of the previous year (-0.270 , $p < 0.05$). During the current growing season, NTMSTD and NTMRES did not show significant responses to temperature, while the HBYSTD and HBYRES chronologies were significantly negatively correlated with the average temperature from May to June of the current year, especially with the highest correlation at the Taibai meteorological station (-0.358 , $p < 0.01$). The combinations of temperature during the growing season at the Taibai station were all significantly negatively correlated with the HBYSTD chronology (Table 4), while the precipitation combinations generally showed

positive correlations, with the highest correlation coefficient 0.267 ($p < 0.05$) of the total precipitation from May to July of the current year.

Table 2. Correlations between Huangbaiyuan (HBY) chronologies and climatic factors.

Month	HBYSTD vs. Thz	HBYSTD vs. Phz	HBYSTD vs. Ttb	HBYSTD vs. Ptbt	HBYRES vs. Thz	HBYRES vs. Phz	HBYRES vs. Ttb	HBYRES vs. Ptbt
P5	−0.177	0.065	−0.221	0.094	0.005	0.063	0.006	0.085
P6	−0.086	−0.033	−0.247	0.069	−0.058	−0.155	−0.164	−0.079
P7	−0.030	0.009	−0.068	−0.001	−0.007	−0.012	−0.070	−0.151
P8	−0.215	0.168	−0.271	0.187	−0.201	0.143	−0.198	0.180
P9	−0.107	−0.100	−0.136	−0.089	−0.060	0.006	−0.015	−0.096
P10	−0.151	−0.170	−0.218	−0.164	−0.182	−0.155	−0.142	−0.211
P11	0.086	−0.111	0.033	−0.058	−0.012	−0.133	−0.039	−0.075
P12	0.031	−0.005	0.119	−0.149	0.093	0.071	0.194	−0.126
C1	0.101	0.293 *	0.063	−0.057	0.198	0.256	0.063	−0.095
C2	0.077	0.126	0.099	0.038	0.046	0.064	0.106	0.100
C3	−0.043	0.118	−0.038	0.123	−0.012	0.061	0.015	0.056
C4	0.147	−0.204	−0.009	−0.144	0.253	−0.103	0.170	−0.052
C5	−0.348 **	0.043	−0.404 **	0.034	−0.369 **	0.075	−0.402 **	0.116
C6	−0.032	0.103	−0.136	0.199	−0.006	0.026	−0.108	0.194
C7	−0.040	−0.027	−0.012	0.236	0.061	−0.066	0.146	0.101
C8	−0.065	0.012	−0.132	0.001	−0.024	−0.108	−0.030	−0.178
C9	−0.047	−0.206	−0.224	−0.046	0.002	−0.126	−0.162	0.046
C10	−0.005	−0.050	−0.207	0.089	0.138	−0.061	−0.043	0.066

Note: * $p < 0.05$, ** $p < 0.01$; P indicates previous year, C indicates current year; Thz and Phz are the mean monthly temperature and the sum of monthly precipitation for Hanzhong meteorological station, while Ttb and Ptbt for Taibai meteorological station (1958–2011).

Table 3. Correlations between Nantianmen (NTM) chronologies and CRU climatic factors.

Month	NTMSTD				NTMRES			
	T	Tmax	Tmin	P	T	Tmax	Tmin	P
P5	−0.025	−0.015	−0.035	0.059	0.004	−0.040	0.080	0.141
P6	−0.120	−0.269 *	0.226	−0.002	−0.222	−0.251	−0.015	−0.017
P7	−0.121	−0.176	0.020	0.028	−0.290 *	−0.270 *	−0.176	−0.098
P8	−0.077	0.005	−0.190	−0.079	−0.031	0.044	−0.158	−0.103
P9	0.199	0.368 **	−0.162	−0.375 **	0.060	0.219	−0.184	−0.173
P10	0.158	0.136	0.106	0.048	0.134	0.195	−0.002	0.015
P11	−0.020	−0.104	0.094	−0.057	−0.044	−0.153	0.110	0.104
P12	0.258	0.293 *	0.175	−0.014	0.187	0.191	0.163	−0.060
C1	0.115	0.053	0.158	−0.073	0.055	−0.032	0.157	−0.174
C2	0.176	0.239	0.047	−0.118	0.080	0.105	0.026	−0.090
C3	0.033	0.075	−0.045	0.010	−0.048	−0.031	−0.063	−0.008
C4	0.039	0.033	0.031	−0.068	0.148	0.155	0.083	0.005
C5	−0.074	0.004	−0.182	−0.078	0.038	0.081	−0.064	−0.036
C6	0.094	−0.060	0.297 *	−0.051	−0.054	−0.100	0.064	−0.226
C7	0.156	0.080	0.191	0.133	−0.063	−0.099	0.013	0.150
C8	−0.106	−0.064	−0.128	−0.008	0.061	0.068	0.014	−0.120
C9	0.232	0.275 *	0.002	−0.288 *	0.249	0.211	0.113	−0.126
C10	0.123	0.006	0.194	0.030	0.111	−0.032	0.220	0.124

Note: * $p < 0.05$, ** $p < 0.01$; P indicates previous year, C indicates current year; T: the average temperature; Tmax: the max temperature; Tmin: the minimum temperature; P: monthly precipitation (1958–2011).

Table 4. Correlations between chronologies of Huangbaiyuan (HBY) and climatic factors on seasonal scales.

Climate Factor	HBYSTD				Climate Factor	HBYRES			
Month	Thz	Phz	Ttb	Ptb	Month	Thz	Phz	Ttb	Ptb
C5C6	−0.275 *	0.098	−0.358 **	0.162	C5C6	−0.275 *	0.065	−0.343 *	0.206
C5C7	−0.216	0.045	−0.290 *	0.267 *	C5C7	−0.170	−0.003	−0.218	0.198
C5C8	−0.203	0.041	−0.281 *	0.199	C5C8	−0.148	−0.057	−0.186	0.032
C5C9	−0.197	−0.056	−0.314 *	0.149	C5C9	−0.132	−0.105	−0.212	0.047
C5C10	−0.176	−0.066	−0.328 *	0.157	C5C10	−0.072	−0.117	−0.192	0.057

Note: * $p < 0.05$, ** $p < 0.01$; C5C6 indicates the average value of May and June in the current year; Thz and Phz for Hanzhong meteorological station, while Ttb and Ptb for Taibai meteorological station (1958–2011).

Both HBY chronologies were used to perform spatial analysis and extreme value determination. The results showed that the HBYSTD and HBYRES chronologies were significantly negatively correlated with the average temperature in May in most areas of the eastern monsoon region of China (Figure 4a,b), and the NTMRES chronology is significantly positively correlated with the precipitation in May and the Standardized Precipitation Evapotranspiration Index (SPEI) in the Qinling and surrounding areas (Figure 4c,d). Extreme high and low ring-width years could reveal the amplitude and frequency of changes in tree radial growth. In this study, the threshold for determining extreme growth conditions recorded by the HBYSTD chronology is set as the mean ring-width index plus or minus one standard deviation ($\text{Mean} \pm 1\text{SD}$) (Table 5). From 1902 to 2015, the mean of the HBYSTD chronology width index is 0.971, with a standard deviation of 0.136, and the extreme value ratio is 1.917. The range of extreme high-value years (>1.107) is 1.124–1.338, accounting for 20 years, and the range of extreme low-value years (<0.835) is 0.698–0.831, accounting for 18 years, accounting for 17.5% and 15.8% of the total years, respectively. The drought and flood index (DFI) showed 10 extreme drought years occurred in the low-value years and 7 extreme flood years occurred in the high-value years, accounting for 50% and 39%, respectively (Table 5).

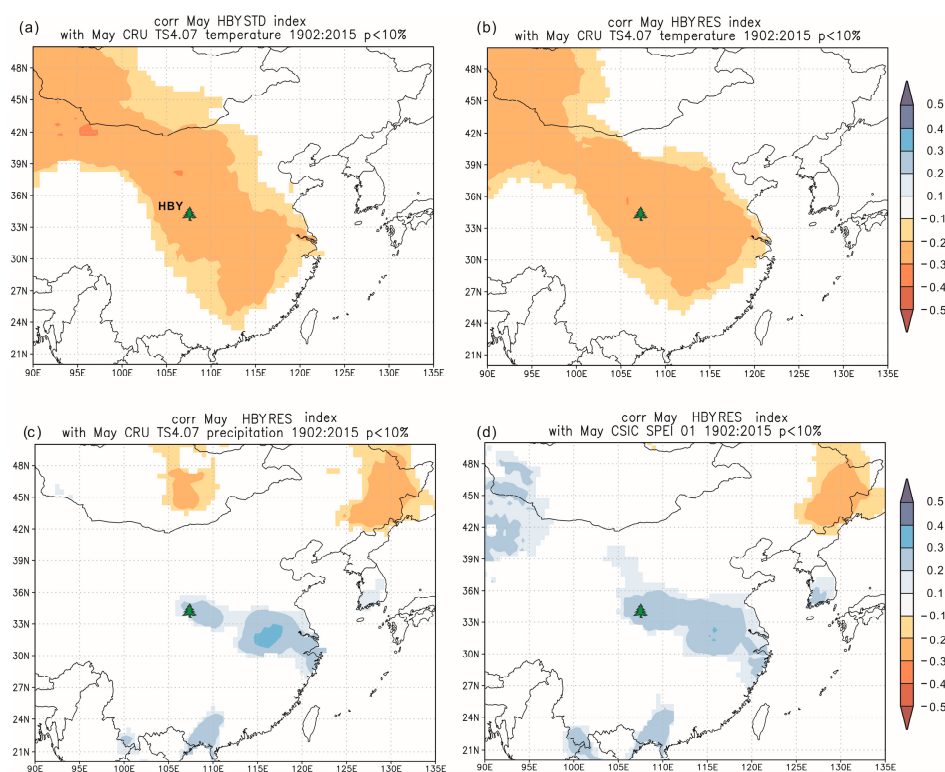


Figure 4. Spatial correlations between Huangbaiyuan chronology and the grid dataset of (a) temperature vs. HBYSTD, (b) temperature vs. HBYRES, (c) May precipitation vs. HBYRES, and (d) SPEI vs. HBYRES on the 1 month scale during the period 1902–2015 ($p < 0.1$). (HBY marked by a green tree).

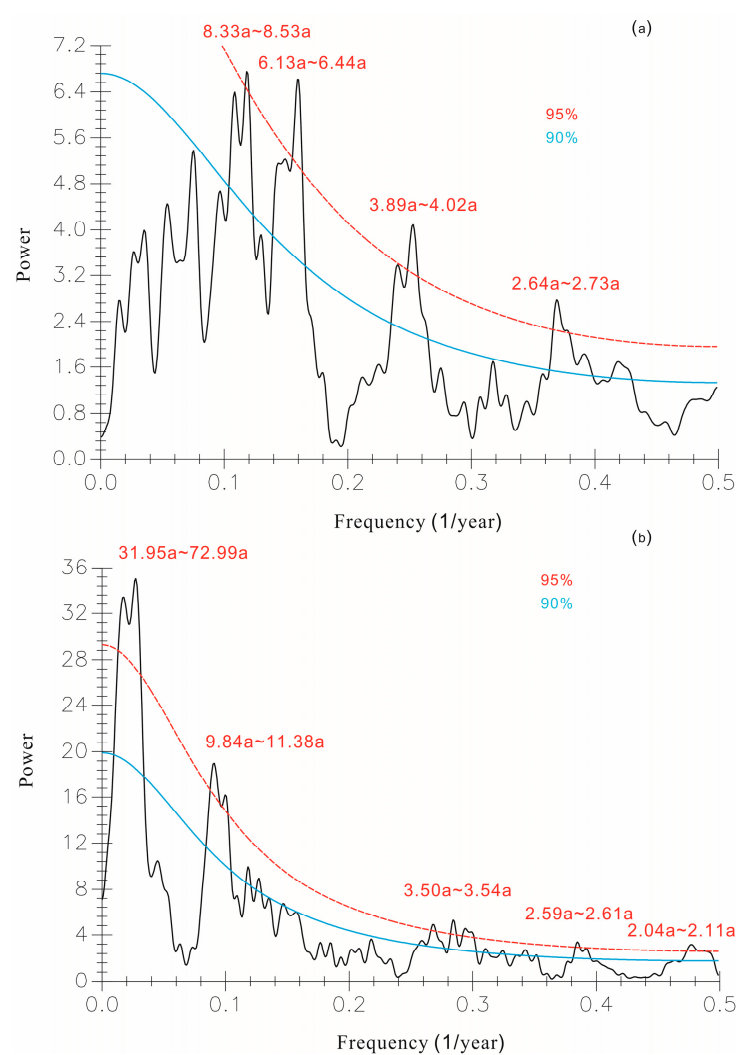
The results of spectral analysis of the multitaper method (MTM) showed that the tree radial growth variation on the southern slope of the central Qinling Mountains had interannual and interdecadal scale fluctuations (Figure 5). The HBYSTD chronology had quasi-periodic signals at 8.33–8.53 years ($p < 0.05$), 6.13–6.44 years ($p < 0.05$), 3.89–4.02 years ($p < 0.05$), and 2.64–2.73 years ($p < 0.05$); the NTMSTD chronology had signals at 31.95–72.99 years ($p < 0.05$), 9.84–11.38 years ($p < 0.05$), 3.50–3.54 years ($p < 0.05$), 2.59–2.61 years ($p < 0.05$), and 2.04–2.11 years ($p < 0.05$).

Table 5. Extreme events inferred from Huangbaiyuan standard chronology (HBYSTD) and drought and flood index (DF index).

Rank	Year	Extreme Low Index	Deviation	DF Index	Year	Extreme High Index	Deviation	DF Index
1	1903 ^a	0.831	−0.004		1906	1.148	0.041	DF_2
2	1919 ^a	0.748	−0.087	DF_4	1914	1.278	0.171	DF_2
3	1920 ^a	0.698	−0.137	DF_4	1933	1.137	0.03	DF_1
4	1927	0.82	−0.015	DF_5	1934 ^b	1.127	0.02	DF_1
5	1928	0.788	−0.047	DF_5	1935	1.14	0.033	DF_2
6	1929	0.814	−0.021	DF_5	1942	1.317	0.21	
7	1950	0.807	−0.028	DF_4	1946 ^b	1.299	0.192	
8	1955	0.81	−0.025		1954	1.126	0.019	
9	1963	0.778	−0.057		1959 ^b	1.254	0.147	
10	1965 ^a	0.79	−0.045		1960 ^b	1.186	0.079	
11	1968 ^a	0.821	−0.014		1974 ^b	1.18	0.073	
12	1969 ^a	0.743	−0.092	DF_4	1975 ^b	1.124	0.017	
13	1970	0.814	−0.021	DF_4	1979	1.129	0.022	
14	1976 ^a	0.702	−0.133	DF_4	1980	1.144	0.037	DF_1
15	1995	0.766	−0.069	DF_5	1990 ^b	1.217	0.11	
16	2003	0.733	−0.102		1991	1.127	0.02	DF_2
17	2004	0.829	−0.006		1993	1.338	0.231	
18	2010	0.767	−0.068		2006	1.137	0.03	
19	2011	0.824	−0.011					
20	2014	0.753	−0.082					

Note: Five grades of DF_1: very wet, DF_2: wet, DF_3: normal, DF_4: dry, and DF_5: very dry. ^a The El Niño year.

^b The La Niña year.

**Figure 5.** Cycles for (a) Huangbaiyuan standard chronology (HBYSTD) and (b) Nantianme standard chronology (NTMSTD).

4. Discussion

4.1. Climate and Tree-Ring Growth Relationship

P. tabuliformis and *A. fargesii* are typical evergreen coniferous species in the vertical vegetation zones of the Qinling Mountains [11,14]. *P. tabuliformis* is a widely distributed coniferous species in the low to mid-altitude regions of the Qinling Mountains, primarily growing at elevations ranging from 1000 to 2200 m on the southern slopes. At approximately 1500 m, the vegetation is dominated by *P. tabuliformis* and *Quercus aliena* forests, with associated species including *Abies chensiensis*, *Betula albosinensis*, and *Quercus variabilis* [23]. The *P. tabuliformis* in Huangbaiyuan is mainly distributed in the pine-oak forest belt below 2200 m, characterized by deep soil layer and good drainage, belonging to the montane deciduous broad-leaved forest zone [23]. *A. fargesii* on the southern slope of Mount Taibai is primarily found on slopes and ridges at elevations of 2500 to 3300 m, often forming pure or mixed forests with *Betula albosinensis* and *Betula platyphylla*, belonging to the subalpine coniferous forest zone [24]. The distribution area of *A. fargesii* forests is predominantly characterized by granite bedrock, with the understory soil mainly consisting of thin layers of dark brown soil. The climatic conditions in this region are cold, humid, and frequently foggy [13]. The radial growth climate response results of these two dominant species could support the scientific management and sustainable utilization of natural forests on the southern slope of the Qinling Mountains [22].

The HBY chronology had a significantly negative correlation with the temperature in May of the growing season ($p < 0.05$) and a positive correlation with the same period's precipitation (not significant), indicating that the moisture condition in May was a main factor in the early stage of radial growth of *P. tabuliformis*. Studies on *P. tabuliformis* in the northern slope of the Qinling Mountains and the Loess Plateau in northern China showed that precipitation in May of the current year was one of the main factors affecting tree growth, although these studies had different time windows for growth response relationships (Figure 1) [38–43]. For example, the TL tree ring chronology from Tianlong Mountain on the eastern Loess Plateau is significantly negatively correlated with the temperature from October of the previous year to September of the current year ($p < 0.05$), with the highest correlation in May (-0.649 , $p < 0.01$) [42]; the WQ tree ring chronology from Wuqi on the northern Loess Plateau is negatively correlated with the temperature during the growing season, with the highest value appearing in May ($p < 0.05$) [43]. Similar monthly response patterns are observed in KT from Mount Kongtong on the western Loess Plateau [38], Mount Quiqing (GQ) [39], Mount Xiaolong (XL) [40], and Mount Nanwutai (NWT) [41] on the northern slope of the Qinling Mountains (Figure 1). The growth response of *P. tabuliformis* at these sites is mainly characterized by a positive response to changes in water conditions during the early stage of the East Asian summer monsoon and the non-monsoon season. The HBY site in this study is located further south and belongs to the subtropical climate. As a non-monsoon period, less precipitation and rapidly rising temperatures in May tend to lead to water deficit; therefore, the drought in May becomes the main limiting factor for *P. tabuliformis* (Figure 3). The lack of significant response in the HBY chronology to the precipitation during the rainy season from July to September indicates that the abundant water supply during the rainy season fully meets the growth needs of *P. tabuliformis* (Table 2). However, the NTM *A. fargesii* chronology shows different response characteristics (Table 3). Figure 3 shows that the precipitation in September is the second-highest monthly precipitation of the year, and this period of precipitation is known as the “Huaxi autumn rain” [44,45], a stable rainfall span appearing in the Qinling Mountains and nearby related to southward movement of the subtropical high in the northwest Pacific in autumn [46,47]. The lower temperature in September leads to reduced evaporation and transpiration, resulting in saturated soil moisture, and this, in turn, restricts root respiratory

activity, causing the radial growth of trees to be inhibited. Therefore, the significant negative (positive) correlation of the high-altitude NTMSTD chronology with the precipitation (max temperature) in September of the previous year and the current year supports the strong limiting effect of September precipitation on tree growth (Table 3). The negative correlations between the *A. fargesii* ring-width chronology and September precipitation have also been reported in the southern slope of the Qinling Mountains [12–14]. In the Shennongjia area, the precipitation of the previous September and the current September significantly inhibits the radial growth of *A. fargesii* [13], while in the Niubeiliang area, the radial growth of *A. fargesii* is significantly negatively correlated with the precipitation of the current September [14]. This indicates that excessive autumn precipitation has a common limiting effect on the radial growth of *A. fargesii* on the southern slope of the Qinling Mountains. The significant negative correlations with the max temperature in the previous June (-0.269 for NTMSTD) and mean/max temperature in July of the previous year (-0.290 and -0.270 for NTMRES, Table 3) indicate the influence of insufficient water during the same period. A significant positive correlation between NTMSTD and the minimum temperature in June of the current year (0.297 , $p < 0.05$) suggested that warm nighttime temperatures in the early growing season are beneficial to the radial growth of trees in alpine areas above 3000 m in elevation.

The current results indicate that the response relationship between tree radial growth and climate factors is different in the two sampling sites, but the related effects of more local environmental variables on the growth response model still need in situ monitoring and exploration in the future [48].

4.2. Extreme Events and Regional Hydroclimate

High temperature leads to increased evaporation and transpiration, which in turn causes soil moisture deficits and droughts, especially against the backdrop of the continuous rise in global temperatures [49]. The HBY chronology shows a significant negative correlation with the temperature during the growing season and a positive correlation with precipitation (Table 4), indicating that droughts caused by water stress inhibit tree radial growth, resulting in narrow rings, and conversely, wide rings are produced. Therefore, the extremely wide and narrow years listed in Table 5 could indicate the dry and wet conditions of the growing season in the study area [18]. The extremely narrow year corresponding to the drought-flood index of DF_5, 1927 ($<1SD$), 1928 ($<1SD$), and 1929 ($<1SD$), responded to the historically extreme drought events that occurred in Shaanxi and the surrounding Loess Plateau region [19,50]. This large-scale, persistent, severe drought covered most of the eastern part of northwestern China, resulting in the deaths of millions of people [18,50]. In comparison, the severe drought that occurred around 1928 in Gansu Province, where the tree-ring sites KT, GQ, and XL are located, led to the death of nearly half of the population due to food shortages [18]. This regional extreme drought period in the 1920s was recorded and responded to in the HBY, GQ, XL, and NWT chronologies (Figure 6). Previous tree-ring studies in the central watershed area of the Qinling Mountains, which are sensitive to temperature variations, have shown that the extremely high ring-width index ($>1SD$) strongly recorded the regional high-temperature drought events represented by 1927, 1928, and 1929 [16]. The other two dry periods of the 1900s and 1990s–2000s recorded in the tree-ring studies on the northern slope of the Qinling Mountains are also captured by the HBYSTD chronology, reflecting the indicative ability of the HBY *P. tabuliformis* on the southern slope of the central Qinling Mountains for regional hydroclimatic signals, thereby proving the reliability of the spatial response results of temperature, precipitation, and the Standardized Precipitation Evapotranspiration Index (Figure 4).

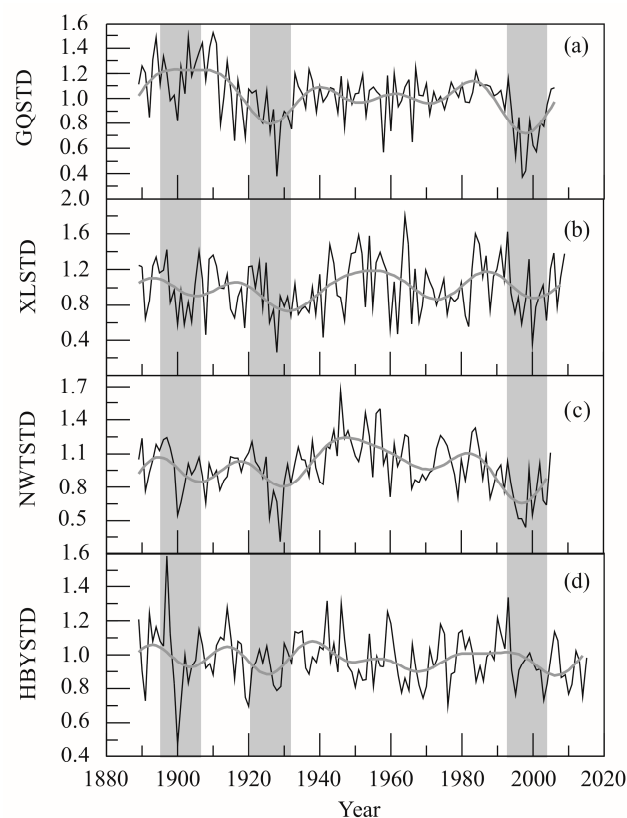


Figure 6. Comparisons of tree-ring records in the central Qinling Mountains (a) GQSTD [39], (b) XLSTD [40], (c) NWTSTD [41], and (d) HBYSTD (this study). The bold line represents the 20-year low pass data. The grey-shaded areas represent severe dry intervals discussed in text.

4.3. Periodicity and Large-Scale Climate Forcing

The interannual and multidecadal periodic signals indicate (Figure 5) that the radial growth of trees on the southern slope of the central Qinling Mountains has been influenced by large-scale climate forcing factors. Tree ring studies at comparative sites TL, LT, GQ, XL, and NWT on the northern slope of the Qinling Mountains and the Loess Plateau have all found similar periodic signals. Among them, the 2–8 year signals may reflect the teleconnection influence of ENSO on the hydrological climate of the study area [17–19,51]. The signals at frequencies of 31.95 years and 72.99 years may reflect the influence of ocean-atmosphere coupling in key maritime areas of the Pacific and Atlantic, such as the PDO and Atlantic Multidecadal Oscillation (AMO). Recent streamflow reconstruction based on tree-ring width and density in the Wei River basin on the northern slope of the Qinling Mountains for the past 400 years also captures the same periodic signals [18]. Previous research has reported that during the positive phases of ENSO and PDO, North China and surrounding areas tend to have high temperatures, less rainfall, and drought weather, while the opposite phases tend to be wetter conditions [52,53]. There are 7 years of El Niño and La Niña occurring in the years of extreme low and extreme high index years, respectively (Table 5), which to some extent reflects the impact of ENSO variations on the dry and wet conditions of the study area [18,41]. The tripole sea surface temperature mode in the North Atlantic could affect the hydrological and climatic conditions of the northern and southern regions of China by exciting the Eurasian teleconnection pattern [54,55]. Correlation analysis shows that the HBYSTD and NTMSTD chronologies are significantly correlated with the NAO index of the previous November–December and the previous October, with correlation coefficients of 0.220 and 0.202, respectively ($n = 116$, $p < 0.05$, 1900–2015), suggesting that the changes in hydrological and climatic elements reflected

by the tree growth in central Qinling Mountains have a teleconnection response with the North Atlantic [56].

5. Conclusions

Two new tree-ring width chronologies based on *P. tabuliformis* and *A. fargesii* were developed for the southern slope over the central Qinling Mountains. There were differences in the climate-growth response patterns between both two tree species. The *P. tabuliformis* chronology responded to the climatic factors at the beginning of the growing season (May), while the *A. fargesii* chronology responded to the precipitation at the end of the previous year and the current year's growing season (September), as well as the hydrological and climatic factors of the previous growing season. The radial growth of *P. tabuliformis* could reflect regional extreme dry and wet events and had a certain representativeness of regional climate change. Both chronologies contained interannual and multidecadal periodic signals, indicating that the hydrological and climatic changes in the central Qinling Mountains were teleconnected with the atmospheric drivers of key oceanic areas, such as ENSO, PDO, and NAO.

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