Assessing the Sensitivity of Young Pine Trees (*Pinus tabuliformis*) to Climate Change at Moisture Stressed Sites in the Qinling Mountains, Central China

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Abstract

In dendroclimatic studies, it is generally assumed that the relationships between the climate factor and tree-ring variations are stable over time. However, a strong age-related growth trend was found in the earlier part of the chronology and may result in time-dependent variance and climate signal changes. In this paper, the tree-ring width chronologies were developed to assess the sensitivity of young pine trees (*Pinus tabuliformis*) growing at moisture stressed sites in the natural secondary forests of the Qinling Mountains, China. The analysis shows that total February–June precipitation is the main factor limiting the radial growth of young pine trees within our study area. Based on the relationships derived from climate response analyses, the potential of tree-ring chronologies of young pine trees to provide precipitation reconstructions in the Qinling Mountains has been established. Similar with old pine trees, young trees in the natural secondary forest of the Qinling Mountains also can capture the precipitation signals accurately. These results also suggest that tree-ring data from moisture stressed sites in relatively humid environments may be regarded as proxies of drought variability.

Key words: *Pinus tabuliformis*; tree rings; the Qinling Mountains; secondary forests; climate response.

Introduction

The radial growth of trees is often affected by the environment and climate changes, and many scientists have published papers about the response of different species to climatic change and reconstruction of past climate based on tree-ring width chronologies (Büntgen et al. 2007, Papadopoulos et al. 2009, Cook et al. 2010, Chen et al. 2013a, 2014a, 2015a). Many dendroclimatic studies have focused on trees growing in the cold or dry environment because the tree growth is expected to be more sensitive to climate changes under some severe conditions (Esper 2000, Chen et al. 2012, Briffa et al. 2013). In rather warm and wet region of eastern China, however, the radial growth of trees has been considered not to be as sensitive to climate factors. Therefore, study sites were often chosen in high elevations or in the areas of northern exposition, where expecting temperature to be a limiting factor of tree growth (Zheng et al. 2012, Wang et al. 2013, Chen et al. 2015b, c).

The Qinling Mountains are located in the climate boundary between subtropical and warm temperate zones in China. The warm and humid environments of the Qinling Mountains are not advantageous to obtain good samples for dendroclimatological study. However, recent works are gradually extending the possibility of dendroclimatological study in the Qinling Mountains. Chen et al. (2015c) developed the ring-width chronology of *Abies chensiensis* from the eastern Qinling Mountains, and reconstructed past February–June temperatures in the region. Liu et al. (2013) developed the chronologies of Chinese pine (*Pinus tabuliformis*) and discussed the temperature variation of the southern and northern slopes of the central Qinling Mountains. Chen et al. (2015d) developed tree-ring width chronology of pine (*Pinus tabuliformis* and *Pinus armandii*) trees in Huashan and indicated that precipitation signals could be extracted from the tree-ring chronology. These climate reconstructions make it possible to describe the climate history of the Qinling Mountains. However, only a few species have been surveyed in the Qinling Mountains for developing the chronology to discuss the effect of climate on tree growth. Meanwhile, is the earlier part of the chronology (young trees (< 100 years old)) able to capture the climate signals accurately? If no, it would question the overall ability of tree-ring-based climate reconstructions to capture the climate signals of earlier periods.

The purpose of the present study is to clarify the influence of temperature and precipitation on tree-ring widths of young trees of Chinese pine growing in the natural secondary forests of the Qinling Mountains, China. A comparison of the climatic responses of tree-ring widths between different sites should help to clarify the impact of temperature and precipitation on the radial growth of pine trees growing under specific conditions with microscale variations and to identify mechanisms that control radial growth. Furthermore, the comparison between the tree-ring series of young and old trees developed for this study area allows us to assess for the usefulness of young pine trees in providing stable climate reconstructions.

Material and Methods

Sampling sites

Dry soil site (Lixi, site code LX). At this site (Figure 1), tree-ring cores were collected from pine trees from 1,520 to 1,550 m a.s.l. in July 2012. The LX is located on a southeast facing slope (slope inclination ranges from 5 to 20°) with thin and dry soils, surrounded by the broadleaf forests. The biophysical environment implies that tree growth is limited by moisture availability. In total, 33 cores from 20 trees were collected at breast height (1.3 m) in two opposite directions.

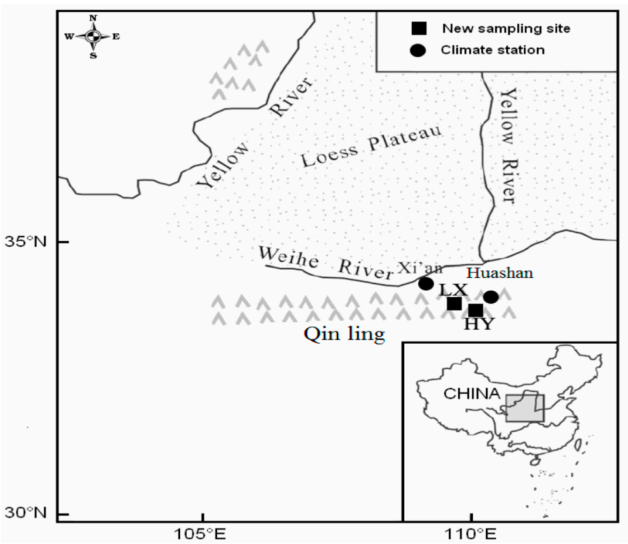

Figure 1. Location map of Lixi (LX), Huayang (HY) and meteorological station

Rocky soil site (Huayang, site code HY). This site (1,450–1,500 m a.s.l.) was located within a river valley near Huashan. Forest canopy closure of this site ranged between 0.2–0.5, and slopes ranged from 5° to 20°. This area is also a dry area in the Qinling Mountains, and open canopy trees with sparse vegetation between each tree, an indicator of drought stress, grow on the rocky soils. In total 43 cores from 22 trees were collected. Site information, including latitude and longitude and slope exposition, is listed for each of the two sites in Table 1.

Table 1. Information about the sampling sites in the Qinling Mountains

Site code	Latitude (N)	Longitude (E)	Elevation (m)	Slope	Aspect
LX	34°17′	109°59′	1520-1550	5–20°	SE
HY	34°29′	110°01′	1450-1500	5–20°	W

Chronology development

After air-drying, the cores were mounted on the wooden mounts and polished with fine sandpaper and a razor blade. The annual rings of each core were measured to the nearest 0.001 mm with a TA Unislide Measurement System (Velmex Inc., Bloomfield, New York). The tree-ring width series from the two sites were cross-dated visually by using skeleton plot procedures and confirmed by a statistical method to ensure that the correct date was assigned to each annual ring (Fritts 1976). Statistical cross-dating was performed with the COFECHA program (Holmes 1983). We used the computer program ARSTAN to detrend the cross-dated tree-ring sequences using a negative exponential curve and to average the detrended ring-width sequences into the tree-ring width chronologies for the two sites (Cook and Kairiukstis 1990). All series of the two sites were then applied to develop a new regional tree-ring chronology (RC) for regional climate analysis. We use the residual version of all chronologies in this study.

Climate data and statistical analysis

The correlation analysis was used to investigate the relationship between tree rings and climate factors. Climate data used for this analysis included monthly mean temperature, total monthly precipitation, and monthly mean Palmer Drought Severity Index (PDSI) over a span of 15 months (from July of the previous year to September of the current year). Instrumental climate records of Huashan (34°29′ N, 110°05′ E, 2064.9 m a.s.l.) during the period 1960–2012 were obtained from the China National Climatic Data Centre. PDSI data was obtained from the Climatic Research Unit (CRU), East Anglia, UK (http://www.cru.uea.ac.uk; 0.5°×0.5°) for the study area for 1960–2012 (averaged over 34.0–35.0°N, 109.5–110.5°E; Van der Schrier et al. 2011).

To assess the potential for climate reconstruction, the simple linear regression models were used to estimate the climate from tree-ring chronologies. A split calibration-verification scheme was employed to test the reliability of the climate reconstruction (Cook and Kairiukstis 1990). The statistics used to test the reliability of the reconstruction models included the reduction of error and coefficient of efficiency statistics, sign test of the original and first-order difference series, and the Pearson's correlation coefficient (Fritts et al. 1990). The reduction of error and coefficient of efficiency examine the strength of the association between actual and estimated values. The sign test shows whether or not sufficient similarity exist between the actual and estimated data sets. They account the number of times that the estimated and observed values are on the same side of the dependent data mean or they are on opposite side of the mean. The detailed explanation of these tests is given in Fritts (1976). We also compare the tree-ring series of young pine trees from the study area with the tree-ring series for Huashan based on the tree-ring width data of old pine trees (> 100 years old) (Chen et al. 2015d) to assess for the usefulness of young pine trees in providing climate reconstructions.

Results

Tree-ring width chronology

The tree-ring width chronologies are shown in Figure 2. A summary of the standardized chronologies is given in Table 2. Tree-ring width chronologies exhibit relatively low mean sensitivities (0.20–0.22) and standard deviations (0.17–0.22). These data indicate rather moderate interannual variations in the ring-width series. The variances in the first eigenvector (37.3–51%) indicate that rather moderate common signals exist among trees. The tree-ring series of the rocky soil site (HY) shows higher variances in the first eigenvector than the tree-ring series of the dry soil site (LX). The first-order autocorrelation of tree-ring width chronologies from the LX and HY site is -0.16 and -0.01, respectively. The chronologies were truncated prior to 1948 (HY), 1960 (LX) and 1948 (RC), respectively, based on the minimum tree number (4 trees).

Table 2. Summary of statistics for tree-ring width chronologies of *P. tabuliformis*

	Tree-ring width index		
	LX	HY	RC
Mean sensitivity	0.22	0.20	0.20
Standard deviation	0.18	0.17	0.22
First order autocorrelation	-0.16	-0.01	0.10
Variance in first eigenvector	39.9%	51%	37.3%
Signal-to-noise ratio	11.56	10.33	7.22
First year where tree number is > 4	1960	1948	1948

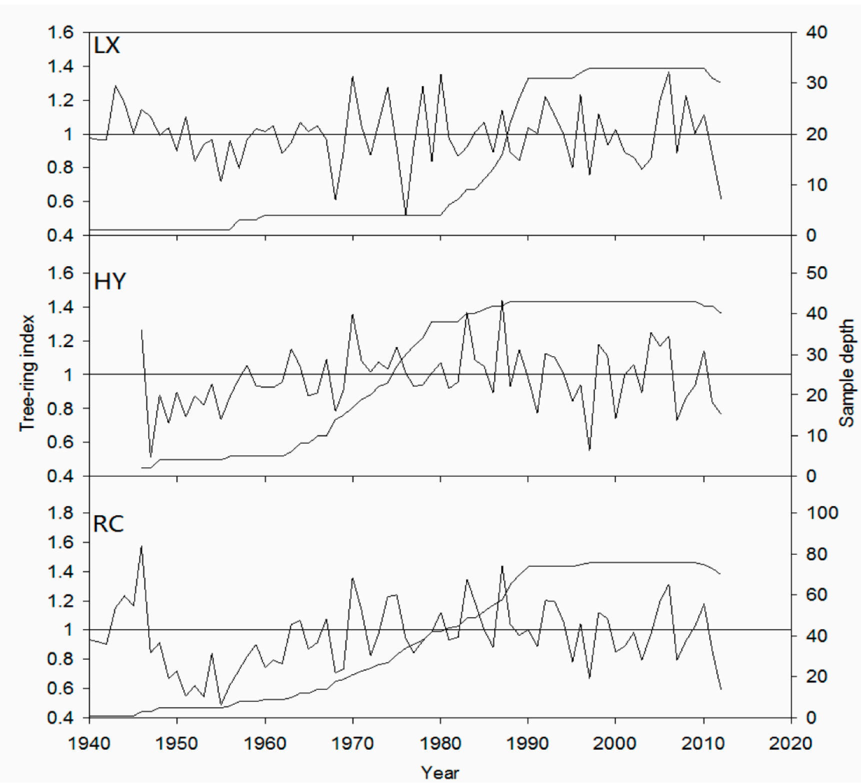

Figure 2. Individual site and regional (RC) residual chronologies of *P. tabuliformis* with sample depth from the Lixi (LX) and Huayang (HY) sites in the natural secondary forests of the Qinling Mountains

Tree-ring width chronologies and their relationship with climatic variables

The tree-ring width chronology of LX site correlates positively with May–June precipitation of the current growing season and temperatures of current April (Figure 3). Moreover, tree growth also correlates positively with PDSI of current July. All the above-mentioned correlations are significant at the 95% level in two-tailed tests; PDSI from prior July to current September are significant at the 99% level.

We found strong positive correlations between the tree-ring width chronology from the HY site and precipitation of current May and June. The tree-ring width chronology from the HY site is also negatively correlated with temperature of prior July, current May and June. Moreover, correlations between the tree-ring width chronology from the HY site and PDSI from May to current September are found to be significant. The RC chronology is negatively correlated with the temperatures of current March, May and June, and positively correlated with the precipitations of current May and June, with significance at 95% level for the correlation analyses. Moreover, the RC chronology has a strong positive relationship to PDSI from May to September.

Generally, past experience indicates that as seasonally averaged climate factors is more representative than just one single month, we used the seasonally average climate factors for further analysis. We screened the tree-ring width chronologies in correlation analysis with the seasonal combinations of temperatures, precipitation and PDSI from the previous July to current September. The RC chronology shows significant positive response to

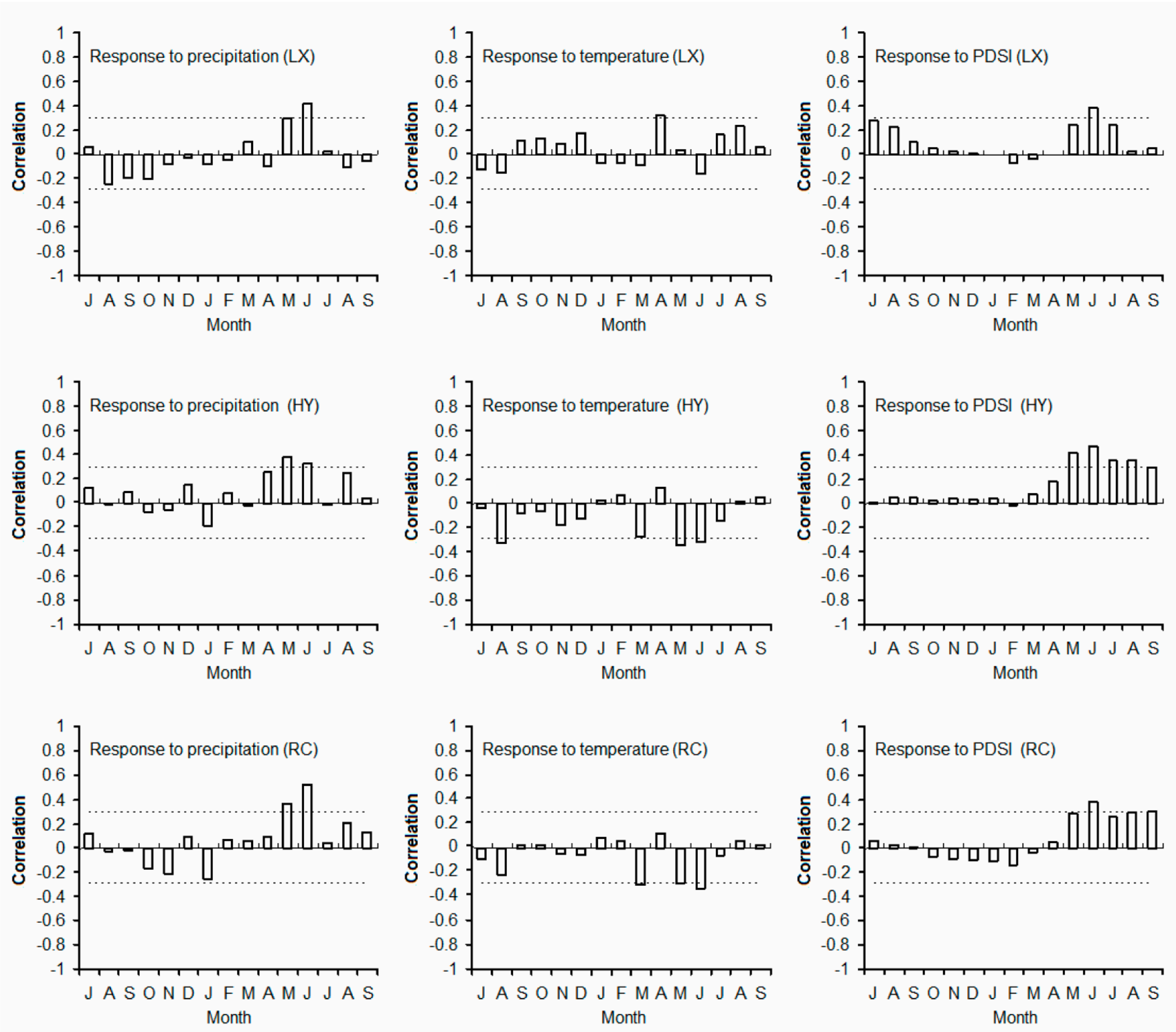

Figure 3. Simple correlations of the residual chronologies with the monthly climate data (precipitation, temperature and PDSI) from previous July to current September over their overlapping periods. The dotted lines indicate significance limits (p<0.05)

precipitation. The highest correlation was found between the RC chronology and total February–June precipitation (r = 0.63, n = 53, p <0.001).

Assessment of potential for precipitation reconstruction

Based on the above climate response analysis results, total February–June precipitation is the most appropriate seasonal predictand for reconstructions (Figure 4). The linear regression model between the RC chronology and total February–June precipitation for the 1960–2012 calibration period was significant (F = 33.47, P < 0.0001). The period from 1960 to 1986 was used for calibration and 1987–2012 for verification; this process was then reversed. The variance explained by the regression on tree-ring variables during the period 1958–2012 for total February–June precipitation is 40.0% (p < 0.001). The statistical properties of verification tests and calibration equations are presented in Table 3. During the verification period (1960–1986), the correlations between estimated and observed series are significant (r = 0.64, p < 0.01) indicating good reliability for the reconstructed series. Positive values for the reduction of error and coefficient of efficiency indicate stability of the reconstruction. The results of sign test also show high values in the precipitation reconstruction.

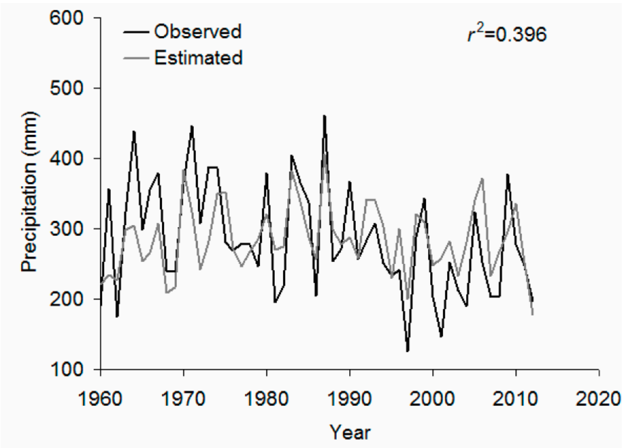

Figure 4. Observed and reconstructed total February-June precipitation for AD 1960–2012

Discussion

Responses of Chinese pine to climatic factors

The strong correlation of Chinese pine with pre-monsoon climate is linked with drought stress occurring during the early part of the growing season. Figure 5 shows the average monthly temperature and precipitation of Huashan climate station based on long-term averages. The temperature begins to increase in March, and April–June is a relatively dry period. Although July is the hottest month of the year, drought stress is no longer a problem because of the onset of the summer monsoon. However, during the pre-monsoon (February–June) and monsoon (July–September) season, total precipitation of the Qinling mountains is highly variable (Figure 5), and many low precipitation events of the Qinling Mountains coincide with the Asian summer monsoon failure (Chen et al. 2013b). Such high interannual variability may involve sev-

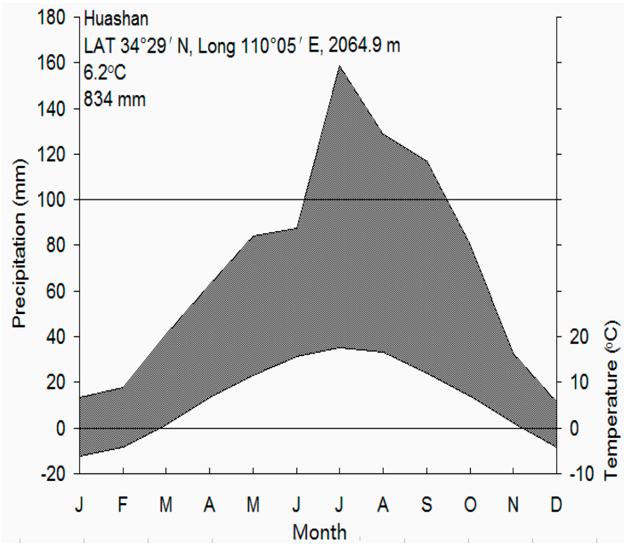

Figure 5. Climate diagram for Huashan meteorological station

Table 3. Calibration and verification analysis of reconstructed February–June precipitation using the RC chronology

	Calibration (1960–1986)	Verification (1987–2012)	Calibration (1987–2012)	Verification (1960–1986)	Full calibration (1960–2012)
r	0.64	0.70	0.70	0.64	0.63
r^2	0.41	0.49	0.49	0.41	0.40
Reduction of error		0.37		0.30	
Coefficient of efficiency		0.25		0.17	
Sign test		21+/5-		20+/7-	
First-order sign test		18+/7-		19+/7-	

eral instances of favourable or unfavourable water availability, leading to the high sensitivity of tree-growth to the precipitation variations of the Qinling Mountains. Chen et al. (2013b, 2014b) demonstrated the extreme years of low precipitation and high temperature and corresponding lower tree growth in Chinese pine in the western Qinling. These studies revealed that pine trees produce narrower tracheids if water is scarce, and the proportion of cell wall in the annual ring increases because of the reduction in lumen size, when tracheids become narrower. Smaller diameter also contributes to smaller ring width, because the ring width is the sum of radial diameters of the tracheids. During a wet phase, the opposite situation occurs.

The correlations between the growth of Chinese pine trees and May-June temperature were negative. High temperatures during the growing season might accelerate the respiration and transpiration rate of trees and simultaneously decrease carbohydrate storage in the stem, and exacerbate the large moisture deficits in the soil. Although annual rainfall averages between 500 and 800 millimetres in the Qinling Mountains, due to the low moisture-holding capacity of dry and rocky soils, the drought–growth correlations at the extreme sites are expected to be high, which may account for the high precipitation–growth correlations in the Qinling Mountains. The precipitation data in our study region represent local drought conditions well and are strongly correlated with the growth of Chinese pine (Chen et al. 2015d). Improved climate understanding depends on future collections of tree-ring samples from moisture stressed sites in the Qinling Mountains.

Comparison between precipitation records from young and old trees

The above analysis of calibration and verification indicates that the calibration equation based on tree-ring width data of young trees also can provide useful estimates of the precipitation history of the study area. Based on tree-ring width data of 127 old trees from Huashan, the precipitation reconstruction of the study area prior to the instrumental period has been developed (Chen et al. 2015d). To assess the similarities and differences between precipitation signals in young and old trees, we compared the RC chronology (this study) with tree-ring width series of old trees from Huashan (Chen et al. 2015d). The RC chronology compares well with tree-ring width data of old trees from Huashan, with $r = 0.61$ ($n = 53$, $p < 0.001$) on the annual scale. The wet and dry events in both curves agree with each other on the decadal scale, showing similar precipitation variability though with the tree age and altitude differences (Figure 6). The synchronous variations in the two series suggest that young trees are also able to capture the drought signals accurately under some severe conditions.

The recruitment of Chinese pine and anthropogenic activity

The growth of Chinese pine does not seem to be modulated only by climatic factors, but also by other controlling factors (i.e. human impact) in natural secondary forests of our study area. This is supported by the recruitment of new saplings. The age structure of the saplings population from 20 to 40 could be explained with cutting disturbance. Since the 17th century, the 800 ha of cleared forest land were used for farming, and the population of our study area increased by 5 times. Especially in the mid 20th century, a state forest farm began to cut mainly *P. tabuliformis* stands of the study area. All related activities were performed in situ: timber from Chinese pine trees was the main resource for heating, housing and lighting. Chinese pine timber, rich in oleoresin, was used to build construction, railway sleepers, pillars, bridges, tools and so on. After the long-term timber harvesting, it has been difficult to see more than 100 years-old Chinese pine in the relatively low altitude areas. Since 1999, timber harvest pressure started to decrease and a further decline of the anthropogenic activities coincided with the implementation of China's Natural Forest Protection Project in 1999. Of particular interest is that the growth of young pine trees maintained a higher sensitivity to precipitation ($r = 0.70$, 1987–2012) than the period 1960–1986, and showed an upward trend during the period 1995–2012.

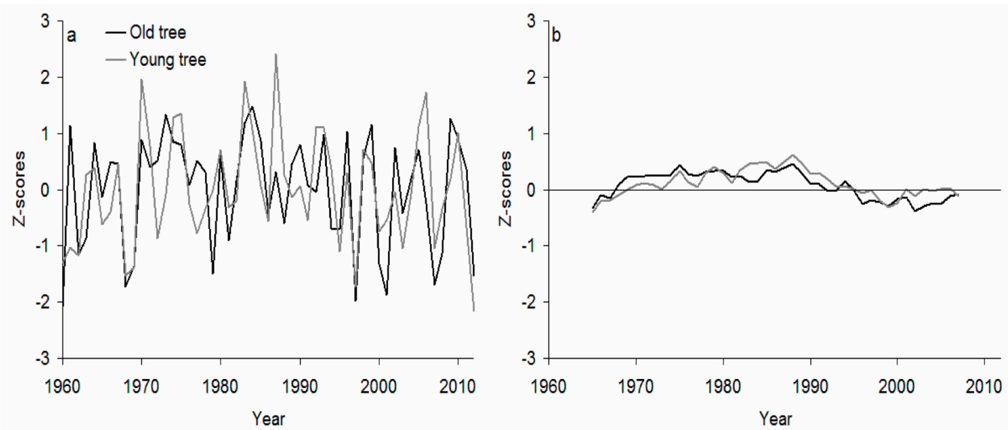

Figure 6. (a) Comparison between the RC chronology and tree-ring width series of old trees from Huashan. (b) Comparison between the 11-year moving average values of RC chronology and tree-ring width series of old trees from Huashan

In contrast, due to religious and topographical reasons, Huashan retained some well preserved old pine forests, and the age of many pine trees is over three hundred years old. The tree-ring index of the old pine trees of Huashan exhibited relatively low radial growth since 1990s (Figure 6b). In addition to the decreased monsoon precipitation (Chen et al. 2015d), tourism activities are an important factor influencing the growth of old pine trees (Zhang and Zhao 2009). Along with the high-speed economy development since 1980s, Chinese tourism industry has been developing rapidly. Due to its outstanding natural values, Huashan is one of the most popular tourist regions in China and suffer the greatest volume of tourist traffic per unit of any area. There are more than 2 million tourists visiting Huashan each year. The soil compaction and mechanical damage to root systems due to trampling effects of the excessive number of tourists has some negative impacts on the old pine trees growing along the access roads. Some dead pine trees are found along the access roads. As was shown in our study, the influences of tourist traffic are also recorded in tree rings of old pine trees as a decrease in the growth dynamics.

Conclusions

We have developed the tree-ring width chronologies of young pine trees (*Pinus tabuliformis*) at the two sites in natural secondary forests of the Qinling Mountains. This study examines the potential utility of tree-ring widths of young pine trees for dendroclimatic studies. The climate response analysis shows that tree-ring widths of young pine trees can potentially be exploited as indicators in dendroclimatological studies because of their strong responses to precipitation. The sensitivity of recent tree-growth of young pine trees to precipitation at the moisture stressed sites of the Qinling Mountains was not significantly reduced under climate warming. Similarly to old pine trees, tree rings of young trees also allow detecting the recently observed precipitation trend. In the future, considerable efforts will be paid to develop more comprehensive tree-ring networks from moisture stressed sites in relatively humid environments to shed more light on the past drought variability of Eurasia over long temporal and large spatial scales. We also suggest that orderly development of tourism and forestry are playing a positive role in preserving the forest stands.

Acknowledgments

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