



Dendroclimatic Response of *Picea crassifolia* along an Altitudinal Gradient in the Eastern Qilian Mountains, Northwest China

Authors: Gao, LinLin, Gou, XiaoHua, Deng, Yang, Yang, MeiXue, Zhao, ZhiQian, et al.

Source: Arctic, Antarctic, and Alpine Research, 45(4) : 491-499

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: <https://doi.org/10.1657/1938-4246-45.4.491>

BioOne Complete (complete.BioOne.org) is a full-text database of 200 subscribed and open-access titles in the biological, ecological, and environmental sciences published by nonprofit societies, associations, museums, institutions, and presses.

Your use of this PDF, the BioOne Complete website, and all posted and associated content indicates your acceptance of BioOne's Terms of Use, available at www.bioone.org/terms-of-use.

Usage of BioOne Complete content is strictly limited to personal, educational, and non - commercial use. Commercial inquiries or rights and permissions requests should be directed to the individual publisher as copyright holder.

BioOne sees sustainable scholarly publishing as an inherently collaborative enterprise connecting authors, nonprofit publishers, academic institutions, research libraries, and research funders in the common goal of maximizing access to critical research.

Dendroclimatic Response of *Picea crassifolia* along an Altitudinal Gradient in the Eastern Qilian Mountains, Northwest China

LinLin Gao*

XiaoHua Gou*‡

Yang Deng*

MeiXue Yang†

ZhiQian Zhao* and

ZongYing Cao*

*MOE Key Laboratory of Western China's Environmental Systems, Collaborative Innovation Centre for Arid Environments and Climate Change, Lanzhou University, Lanzhou 73000, China

†State Key Laboratory of Cryospheric Sciences, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China

‡Corresponding author: Key Laboratory of West China's Environmental System, Ministry of Education, 222 South Tianshui Road, Lanzhou University, Lanzhou 730000, China.
xhgou@lzu.edu.cn

Abstract

Using tree-ring data collected from five stands of Qinghai spruce (*Picea crassifolia*) along an altitudinal gradient in the eastern Qilian Mountains, northwest China, we investigate the differences of the chronologies' statistical parameters and climatic-growth relationships along the gradient. Our results indicate that the radial growth-climate patterns are similar at all studied elevations, and tree growth in this region is strongly related to drought conditions. Growth-temperature and precipitation correlations reveal very coherent patterns for the four lowest sites, showing significant ($p < 0.05$) correlation with July–August temperatures and August precipitation in the previous year and March temperatures in the current year. For the upper treeline site, the chronology is negatively and significantly ($p < 0.05$) correlated with August temperature and December precipitation in the previous year. In addition, individual chronologies are significantly ($p < 0.05$) correlated with the Self-calibrated Palmer Drought Severity Index for many months. The cross-correlation matrix of the individual chronologies indicates all the correlation coefficients are significant ($p < 0.01$), confirmation that tree growth is predominantly influenced by common climate factors. The outstanding drought periods recorded by the five chronologies took place during A.D. 1860–1875, the 1880s, and 1905–1935. Pluvial periods took place during A.D. 1800–1810 and 1975–1990.

DOI: <http://dx.doi.org/10.1657/1938-4246-45.4.491>

Introduction

Under current global warming conditions, changes in forest ecosystems associated with climate change might result in a reduction in the coverage of trees, soil erosion, grassland degradation and even desertification (Liu et al., 1999; Gou et al., 2008). Therefore, a good understanding of the ecological response to recent climate change is required for effective adaptation of forest management practices and socio-economic development. The altitudinal and physiographic characteristics of the mountain ecosystem are considered to be crucial drivers for the vertical distribution of climate, vegetation, and soil types. Evaluating tree growth over altitudinal gradients is vital to assess and predict the response of forests to future climate changes (Liang et al., 2010a). A few previous studies have been conducted on this topic, but the results have varied among different climate conditions and sites. Some studies have demonstrated that trees at high-elevation timberlines were affected by temperature, while moisture stressed at the low-elevation sites (Di Filippo et al., 2007; Peng et al., 2008). Other research has shown that the radial growth-climate response was consistent at high- and low-elevation sites (Esper et al., 2007; Liang et al., 2010a). However, very few such studies were conducted in the Qilian Mountains (Gao et al., 2013).

The Qilian Mountains (36–40°N, 94–103°E), located on the northeastern edge of the Tibetan Plateau in northwest China, are

bordered by the Tengger Desert and the Badain Jaran Desert in the north and the Qaidam Basin in the south. Generally, the Qilian Mountains are divided into the eastern part, central region, and western part by the Shiyang River, Heihe River, and Shule River basin (Lan et al., 2003). Because the Qilian Mountains are situated in the transition zone between the western arid region and eastern humid zone, and are the main water source for the oases of the Hexi Corridor, climate change research under recent global warming conditions in this area is very important. It will provide the foundation for regional water management, agricultural stability, and socioeconomic development. High-resolution paleoclimate records (e.g. tree-ring series) will improve climate change research in this area, which has been seriously hampered by the lack of long instrumental meteorological records. Several tree-ring-based climatic reconstructions have been published during the past decades on the Qilian Mountains. However, most of these studies were conducted in the central region of the Qilian Mountains (Gou et al., 2005; Liu et al., 2007, 2010; Qin et al., 2010), and only a few in the eastern (Deng et al., 2013) and western Qilian Mountains (Liang et al., 2009a; Yang et al., 2010). The eastern Qilian Mountains are a transition zone between arid and semi-arid regions and are expected to be sensitive to global climate change. Therefore, investigating the growth-climate response of trees in this region will be useful for understanding the impact of climate change and will aid further climate reconstruction.

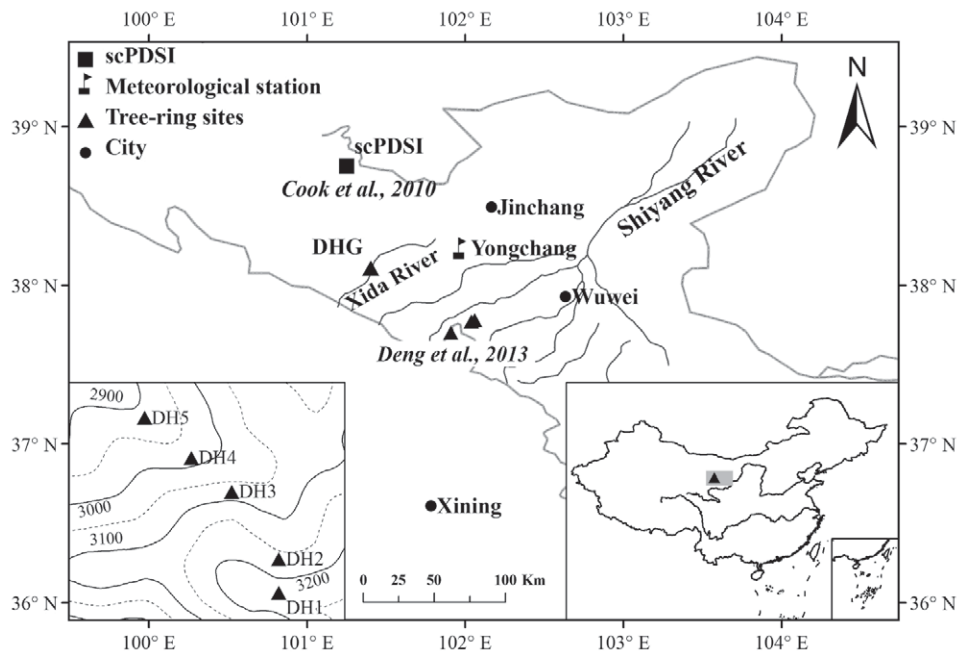


FIGURE 1. The tree-ring sampling site (DHG) and the nearest meteorological station (Yongchang) and scPDSI grid point, and sites from Deng et al. (2013) and Cook et al. (2010) used for comparison. The small figure at the bottom left shows the sampling sites, and the contour lines represent the elevation.

In order to assess the response of the forests to recent climate changes, we explored the dendroclimatic response of trees along an altitudinal gradient using five tree-ring-width chronologies from the Qinghai spruce in the eastern Qilian Mountains.

Material and Methods

STUDY AREA

The sampling sites are located in Dahuang valley (DHG, 38.11°N, 101.40°E), which is a long and narrow valley in the middle reaches of the Xida River in the eastern Qilian Mountains (Fig. 1). The climate in this region is temperate continental arid. Instrumental

records from the nearest meteorological station in Yongchang (38.14°N, 101.58°E, 1976.9 m a.s.l., 1958–2007) show a mean annual precipitation of 200.7 mm and a mean annual temperature of 5.1 °C. The peaks of temperature and precipitation occur in July (Fig. 2). The forest belt ranges from 2700 to 3500 m a.s.l. in the study area. It is dominated by Qinghai spruce (*Picea crassifolia* Kom.) on the wetter, shaded slopes, and Qilian juniper (*Juniperus przewalskii* Kom.) on the drier, sunnier slopes at higher elevations. The dominant shrubs are *Salix oritrepha* C. K. Schneid., *Caragana jubata* (Pall.) Poir., and *Potentilla fruticosa*, while the dominant herbs are *Stipa bungeana* Trin., *Stipa breviflora* Griseb., *Achnatherum splendens* (Trin.) Nevski, *Artemisia* spp., and *Iris lactea* var. *chinensis* (Cheng et al., 2004).

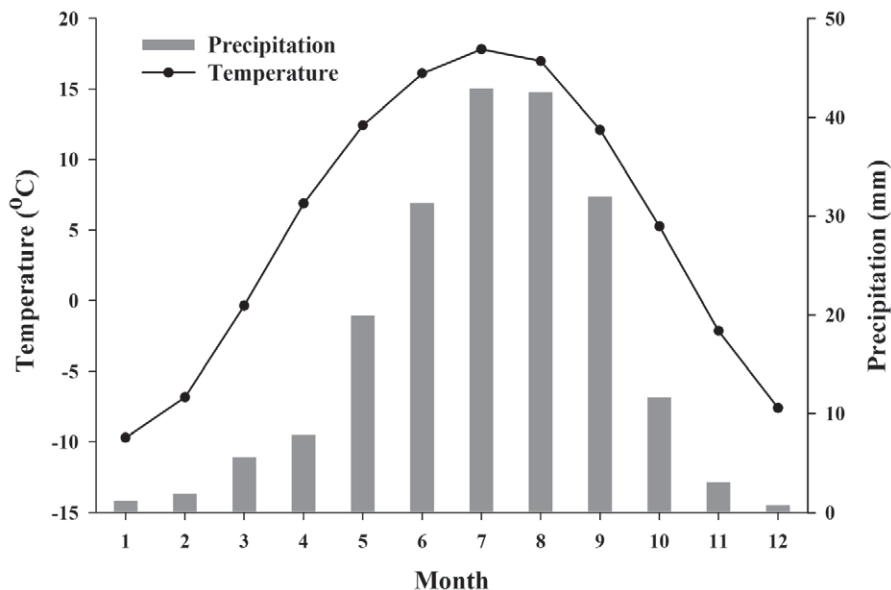


FIGURE 2. Average monthly precipitation and mean temperature at the Yongchang station for 1958–2007.

TABLE 1
Tree-ring sampling sites and climate data used in this study.

Site	Latitude (N)	Longitude (E)	Elevation (m a.s.l.)	Aspect	Slope (°)	Cores/Trees	Time span (A.D.)
DH1	38°06'44"	101°25'08"	3210–3230	North	30–45	71/39	1774–2010
DH2	38°06'49"	101°25'08"	3135–3155	Northeast	30–45	73/40	1775–2010
DH3	38°06'59"	101°25'01"	3040–3060	Northwest	45–55	64/34	1741–2010
DH4	38°07'04"	101°24'55"	2950–2970	Northwest	30–45	63/33	1768–2010
DH5	38°07'10"	101°24'48"	2850–2870	Northwest	30–45	63/39	1793–2010
Yongchang station	38°08'24"	101°34'48"	1976.9				1958–2007
scPDSI grid point	38°45'	101°15'					1958–2010

TREE-RING DATA

Tree-ring samples used in this study were collected from Qinghai spruce (*Picea crassifolia*). Five sites were sampled at approximately 100-m vertical intervals between 2850 and 3230 m (Table 1). The mountain slopes for the five sites are all greater than 30°, and the slope in DH3 is particularly steep (45–55°). The forest canopy density is about 0.3 to 0.5. There are small shrubs under the trees, while the herbs are gramineous. Two increment cores per tree were taken from healthy living trees at breast height (approximately 1.3 m). In total, 334 radii from 185 trees were collected. All the tree cores were taken into the laboratory, and standard techniques of dendrochronology were used to process them (Stokes and Smiley, 1968). After the cores were air dried, mounted, and sanded to a high polish, all the samples were carefully

cross-dated using skeleton plots. Tree-ring widths were measured to 0.001 mm precision with the Velmex measuring system, and the cross-dated measurements were checked using both the TSAP and COFECHA programs (Holmes, 1983; Rinn, 2003). These methods ensured exact dating of each ring-width series.

In order to preserve low-frequency climate signals while removing the age-related growth trends, we used negative exponential functions or linear functions of negative slope to detrend 67–77% of all 118 series at each site. The remaining ~30% of our tree-ring data were detrended using cubic splines with a 50% frequency response cut-off equal to 67% of the length of series. Finally, individual indices were combined into a standard chronology (STD) by the bi-weight robust mean using the program ARS-TAN (Cook, 1985; Cook et al., 2012) (Fig. 3). The subsample

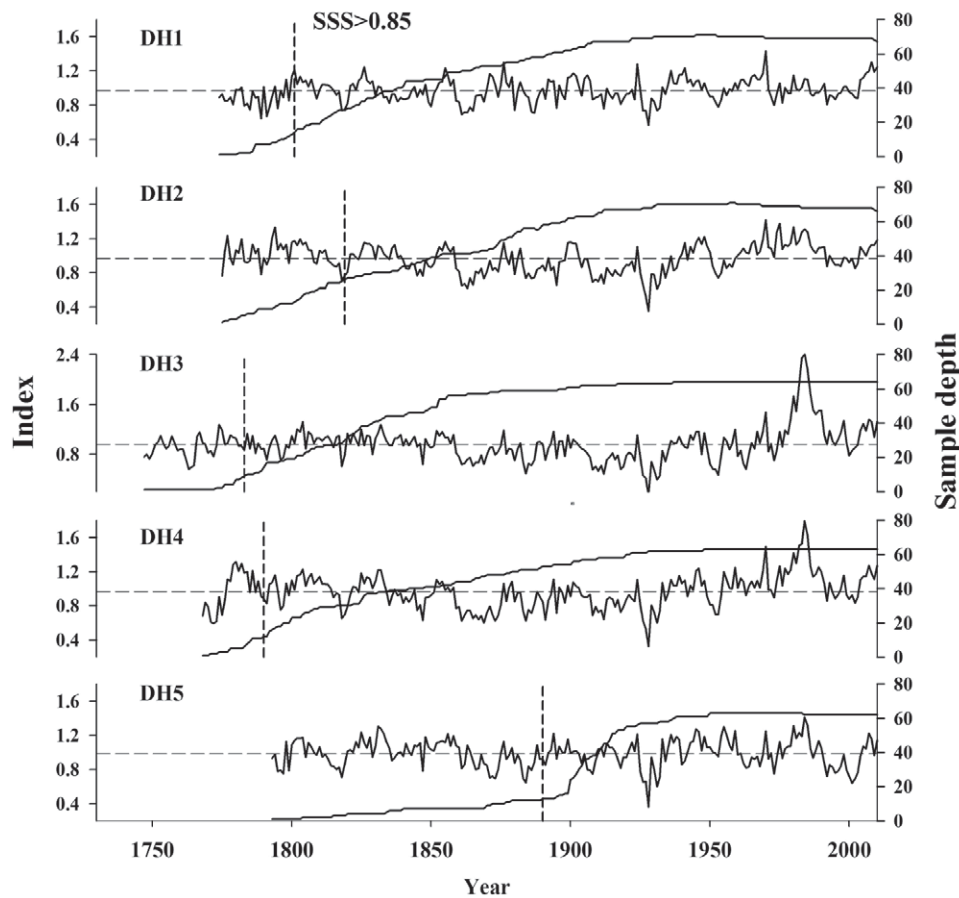


FIGURE 3. The five standardized ring-width chronologies and sample size (number of cores). The vertical dashed lines indicate the starting year of subsample signal strength (SSS) > 0.85.

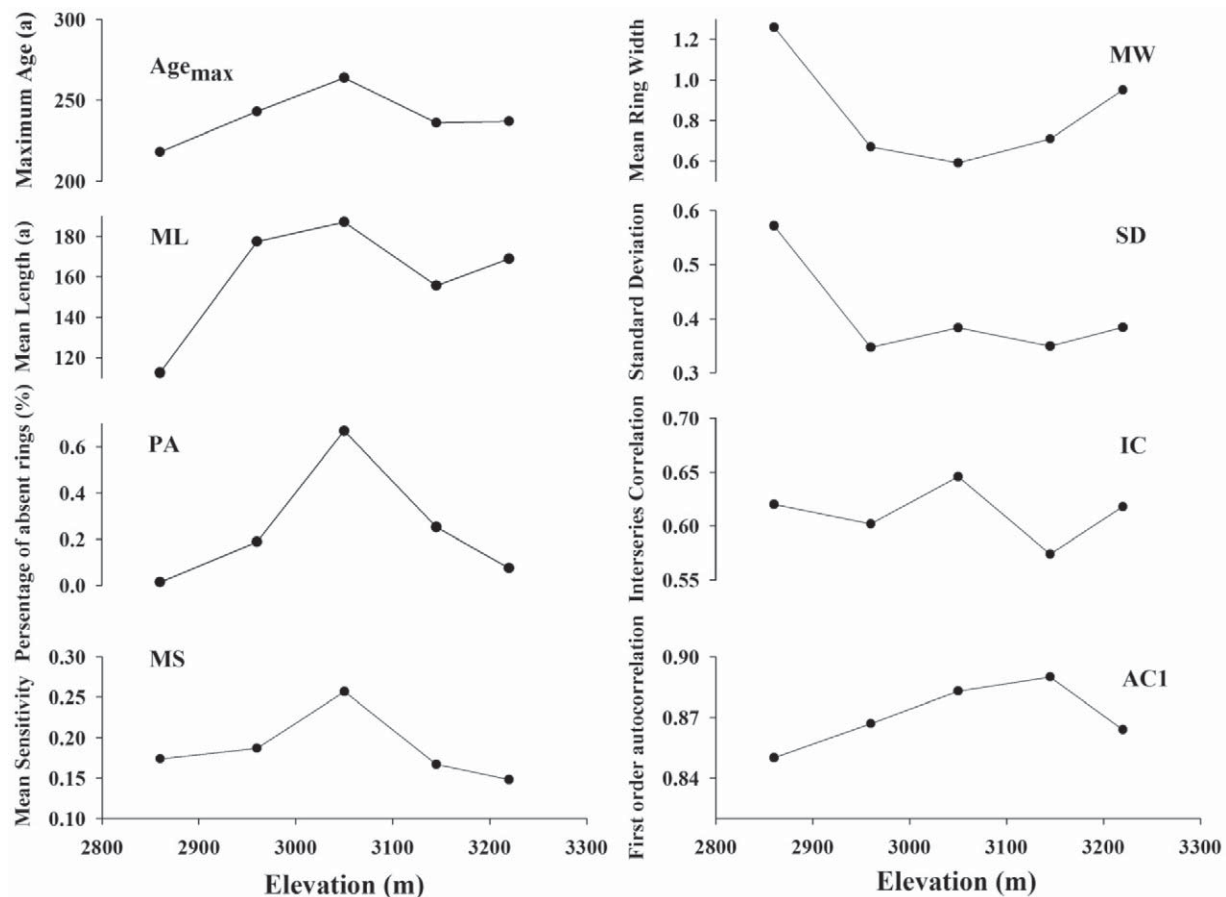


FIGURE 4. Descriptive statistics of the five chronologies along an altitudinal transect. The statistics are: maximum age (Age_{max}), mean ring width (MW), mean series-length (ML), standard deviation (SD), the percentage of absent rings (PA), interseries correlation (IC), mean sensitivity (MS), and first-order autocorrelation (AC1).

signal strength (SSS) statistic was employed with a threshold value of 0.85 to determine the most reliable period of the chronologies (Wigley et al., 1984). Standard statistical parameters of the five ring-width chronologies were evaluated, and these parameters are shown in Figure 4.

CLIMATE DATA

Climate data used in our study were from the Yongchang meteorological station and data from the Self-calibrated Palmer Drought Severity Index (scPDSI) grid point (Dai et al., 2004; Dai, 2011) closest to the sampling sites (Fig. 1). Monthly total precipitation and mean temperature data obtained from Yongchang station were available only for the period 1958–2007. The scPDSI metric was first proposed by Wells et al. (2004). The large differences between PDSI and scPDSI, on regional scales, relates to the inappropriateness of parameters in the “standard” PDSI calculation; scPDSI has been shown to be much more appropriate for characterizing drought conditions than the original PDSI (Van der Schrier et al., 2006a, 2006b). The record of the closest scPDSI grid point to our sampling sites (38.75°N, 101.25°E; Fig. 1) begins in 1935; however, we only used the data during the reliable period of 1958–2010 in order to make comparisons with the nearest meteorological station (Yongchang), which begins in 1958.

Results and Discussion

DIFFERENCES BETWEEN THE CHRONOLOGIES' CHARACTERISTICS

The statistical parameters of the five tree-ring chronologies (Fig. 4) show that the trees growing at the intermediate elevation site (DH3) have the maximum values of mean series-length, tree age, mean sensitivity, mean interseries correlation, and percentage of absent rings, while the mean ring width is lowest. These values may be related to the steep slopes and low soil water storage capacity at this site (Fig. 4, Table 1). At the other four sites (DH1, DH2, DH4, and DH5), the values of percentage of absent rings, mean sensitivity, and maximum age of trees are very similar. The values of mean ring width (1.26 mm) and standard deviation (0.572) for the chronology at the lowest elevation site (DH5) are clearly higher than the other chronologies, while the mean series length at site DH5 is the shortest. All five chronologies showed similar values in their first-order autocorrelation coefficients and mean interseries correlations. The mean interseries correlations are high for all sites (0.574–0.646), indicating that our crossdating is reliable, and the tree growth is synchronous across the stand.

CLIMATE-GROWTH RELATIONSHIPS

Considering tree growth in the previous year could affect the ring-width in the current year, we investigated the correlation rela-

tionships between standard ring-width chronologies and climate factors from May of the previous year to the current October (1958–2007). Results show that the growth-temperature and precipitation correlation patterns are relatively consistent among the five chronologies (Fig. 5). The four lowest sites show a significant negative correlation ($p < 0.05$) with July and August temperatures in the previous year and March temperature in the current growth year. Sites DH3, DH4, and DH5 display a common positive correlation with precipitation in the previous August (though the correlation coefficient is only significant [$p < 0.05$] for DH4). The ring-width chronology from the upper treeline site (DH1) is also significantly correlated with previous August temperature and December precipitation; however, the significant negative correlation with temperatures in the prior July and current March, as reported for the other four chronologies, is not observed. Negative correlations with current year temperatures and positive correlations with pre-

cipitation in the previous July–August indicate the radial growth of trees in this area is limited by moisture conditions. This result is consistent with earlier studies conducted in semi-arid and arid regions (Cai and Liu, 2007; Fang et al., 2010; Tian et al., 2007). Studies by Fritts (1962) in the American Southwest found that the ring width of American beech is inversely related to the severity of drought during August of the previous year, and the latewood width of white oak is inversely related to the severity of drought represented by high temperature in June and high evapotranspiration deficits in July. These results are consistent with the present study, indicating that the tree growth in semi-arid and arid regions is related to the moisture supply during August and temperature of the preceding year. High temperatures in July and August would increase evaporation and reduce soil moisture, which might limit the growth of trees and reduce storage of assimilates for growth in the next year (Liang et al., 2010a, 2010b; Fritts, 1976). Hence,

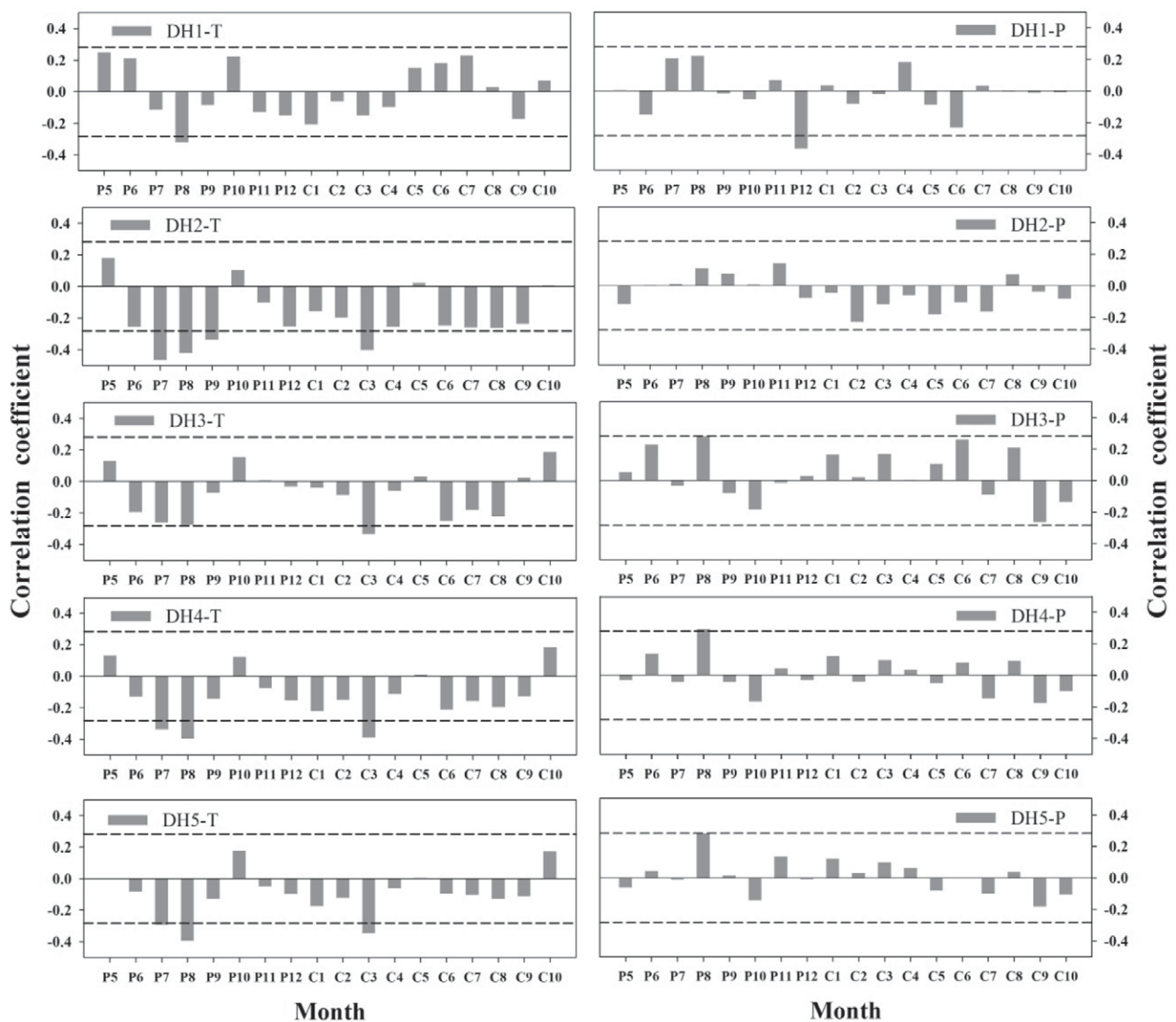


FIGURE 5. The correlation coefficients between the five standardized tree-ring width chronologies and mean monthly temperature (left) and precipitation (right) for 1958–2007. The dashed lines indicate 95% confidence level. (P6 = June of the previous year, C6 = June of the current year, etc.).

ring width in the current growth year shows a negative correlation with July–August temperature and positive correlation with precipitation in the previous year. Fritts (1962) also reported that bud formation and food accumulation in the previous year could produce a lagged growth response. The negative correlation with March temperature in the current year might be related to the respiration of trees. The annual ring width of Qinghai spruce is mainly determined by the width of earlywood, and abundant material storage from the previous year would be beneficial to the formation of earlywood (formed in the second half of the current May) (Venu-gopal and Liangkuwang, 2007; Liang et al., 2009b). Conversely, higher temperatures in March would result in strong respiration in trees and more material consumption, which might be adverse to the formation of earlywood. It is worth noting that the number of statistically significant correlations between precipitation and these chronologies is relatively small, which may be related to differences between precipitation at the sampling sites and the meteorological station. The elevation for Yongchang station is 1976.9 m a.s.l., whereas the elevation of the sampling sites ranges from 2850 to 3230 m a.s.l. The lack of strong correlations between chronologies and precipitation records may also reflect differences in elevation

and vegetation between the forested sample sites and desert location for the climate station. However, due to the lack of weather stations in the high-elevation mountain areas of the arid inland regions of northwest China, we are prevented from using better climate records in this study.

Correlation analysis between the standard chronologies and scPDSI data further confirmed that tree growth in this region is predominantly constrained by drought. As shown in Figure 6, the correlation coefficients between chronologies and the scPDSI data are generally higher and the significantly correlated months are more contiguous than the correlations with temperature and precipitation. This is especially true for the chronology from the lowest elevation site (DH5), which shows a significant ($p < 0.05$) correlation with scPDSI from the prior May to current October (except for July in the current growth year). The strong correlations with scPDSI found in all the chronologies suggest that drought affects tree growth in this area.

While moisture conditions are shown to be the limiting factor for radial growth of trees in the region, our study also found that altitudinal factors have rather weak effects, as similar characteristics and climate-growth relationships are found in the chronologies

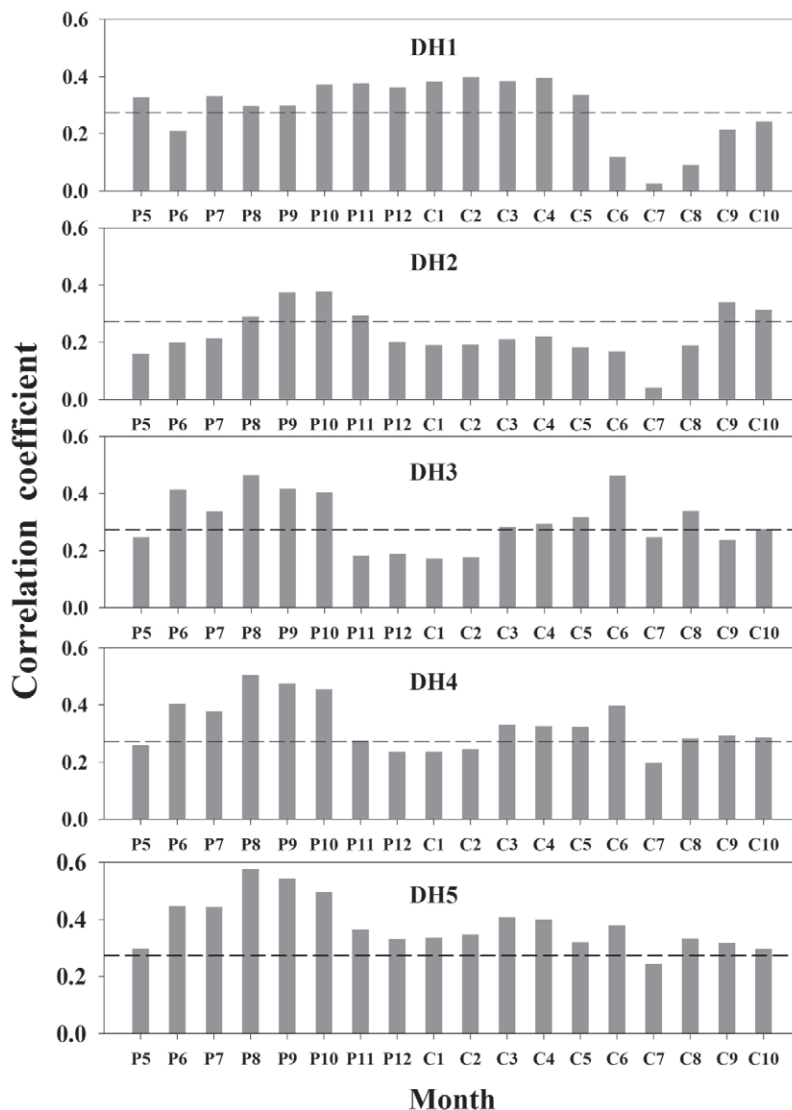


FIGURE 6. Correlations of the five tree-ring chronologies with monthly scPDSI data during 1958–2010. The dashed lines indicate 95% confidence level.

TABLE 2
Cross-correlation matrix of the five chronologies over the 1793–2010 period. All correlation coefficients are significant at the 99% confidence level.

Site	DH1	DH2	DH3	DH4
DH2	0.702			
DH3	0.481	0.695		
DH4	0.617	0.815	0.877	
DH5	0.468	0.528	0.615	0.689

at different elevations. Consistent and significant correlations between tree rings and precipitation/soil moisture along an altitudinal gradient have been reported in other studies of arid regions of northwestern China (Wang et al., 2005), suggesting that tree growth in arid regions is constrained predominantly by moisture conditions. By investigating the growth variation in *Abies georgei* var. *smithii* (Smith fir) along altitudinal gradients (3550–4390 m) in the Sygera Mountains, southeastern Tibetan Plateau, Liang et al. (2010b) showed that the radial growth of Smith fir trees was markedly similar in response to common climatic signals regardless of difference in stand elevation, topographical aspect, and tree age. These results together indicate that climate factors have a more important influence on tree growth than altitude in some regions.

DROUGHT RECORDS BY THE FIVE CHRONOLOGIES

Despite slight differences in the statistical parameters of the chronologies and chronologies' climate-growth relationships, all show similar variation patterns across this altitudinal gradient. Cross correlation between individual chronologies shows that all pairings are significant ($p < 0.05$; Table 2), especially for the chronologies with similar elevations. The strong correlations be-

tween the chronologies confirm that trees in the study area are influenced by common climate factors, and these tree-ring chronologies could be used to investigate past drought variation. We defined wet spells as periods with ring widths above average growth continuously for more than 10 years, and drought spells as intervals with ring widths below average growth continuously for more than 10 years. The common drought periods revealed by the five chronologies are identified as A.D. 1860–1875, the 1880s, and 1905–1935. Common wet intervals occurred during A.D. 1800–1810 and 1975–1990 (some intervals have an exception for one year). Additionally, A.D. 1928 is the narrowest year in all five chronologies, and all chronologies show a trend to wetter conditions since 2000.

When comparing the first principal component (PC1) of the five chronologies to the PDSI reconstructions in the eastern Qilian Mountains derived from Cook et al. (2010) and Deng et al. (2013), we found that the prominent drought periods A.D. 1880–1885, 1925–1933, 1947–1955, and 1997–2003 are consistent in these series (Fig. 7). The drought conditions in our tree-ring records during A.D. 1905–1920 are also consistent with Deng et al.'s (2013) reconstruction as are the drought years A.D. 1793–1798 identified by Cook et al. (2010). However, there also are differences between these tree-ring records, especially during A.D. 1860–1875 and 1980–1990. These discrepancies might be caused by the spatial heterogeneity of drought/pluvial conditions and particularly the use of many remote tree-ring chronologies in Cook's reconstruction (Cook et al., 2010).

Conclusions

Five Qinghai spruce ring-width chronologies from a consistent slope in the eastern Qilian Mountains were used to investigate the radial growth response to climate along an altitudinal gradient. Comparison of the chronologies' characteristics indicates that trees

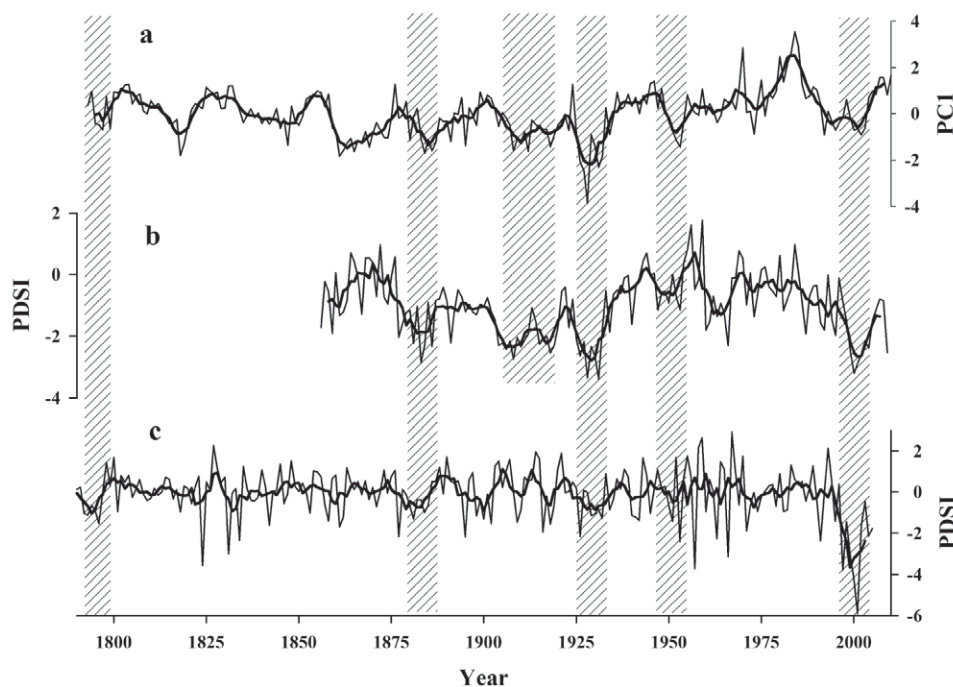


FIGURE 7. The comparisons between (a) the first principal component (PC1) derived from the five chronologies in this study and (b) the Palmer Drought Severity Index (PDSI) reconstructions derived from Deng et al. (2013) and (c) Cook et al. (2010) in the eastern Qilian Mountains. The thick lines represent their 5-year moving average. Consistent dry periods are shaded by bars with diagonal lines.

in the intermediate elevation site (DH3) show the maximum mean sensitivity, maximum age of trees, average interseries correlation, and percentage of absent rings, which is possibly associated with the local conditions (steeper slope and poor soil water storage capacity) at site DH3. Correlation analyses between chronologies and climate factors (temperature and precipitation) display similar climate-growth relationships for the five ring-width chronologies. All four lowest tree-ring stands show significant negative correlation with July–August temperatures in the previous year and March temperatures in the current growth year, and are positively correlated with precipitation in the previous August. For the upper tree-line site (DH1), the radial growth of trees is limited by prior August temperatures and precipitation in the previous December. Negative correlations with temperature and positive correlations with precipitation suggest that trees in this region are mainly influenced by moisture conditions. Correlations with scPDSI for all chronologies further confirm that the growth of trees is predominantly limited by drought. Although there are slight differences in the chronologies' characteristics and climate-growth relationships across this altitudinal gradient, their patterns of decadal-multidecadal variation are very similar. The common drought and wet periods revealed by all five chronologies occurred during A.D. 1860–1875, the 1880s, and 1905–1935 (droughts), and 1800–1810 and 1975–1990 (wet periods), respectively. Comparison between the first principal component (PC1) of the five chronologies presented here and the PDSI reconstructions derived from Cook et al. (2010) and Deng et al. (2013) confirm that there were significant droughts during A.D. 1880–1885, 1925–1933, 1947–1955, and 1997–2003 in the eastern Qilian Mountains.

Acknowledgments

The authors thank Emily Derbyshire for her kind help in editing the English writing. The authors also thank Editor William D. Bowman, Associate Editor Paul J. Krusic, and the anonymous reviewer for their valuable comments and suggestions. This research was supported by the National Basic Research Program of China (973 Program) (No. 2009CB421306), the National Science Foundation of China (41171039 and 41021091), and the Fundamental Research Funds for the Central Universities (Izujbky-2013-250).

References Cited

- Cai, Q. F., and Liu, Y., 2007: January to August temperature variability since 1776 inferred from tree-ring width of *Pinus tabulaeformis* in Helan Mountain. *Journal of Geographical Sciences*, 17: 293–303 (in Chinese with English abstract).
- Cheng, B., Zhu, Y., Chen, F. H., Zhang, J. W., Huang, X. Z., and Yang, M. L., 2004: Relationship between the surface pollen and vegetation in Shiyang River drainage, northwest China. *Journal of Glaciology and Geocryology*, 26: 81–88 (in Chinese with English abstract).
- Cook, E. R., 1985: A time series analysis approach to tree ring standardization. Ph.D. thesis, University of Arizona, Arizona.
- Cook, E. R., Anchukaitis, K. J., Buckley, B. M., D'Arrigo, R. D., Jacoby, G. C., and Wright, W. E., 2010: Asian monsoon failure and megadrought during the last millennium. *Science*, 328: 486–489.
- Cook, E. R., Krusic, P. J., Holmes, R. H., and Peters, K., 2012: Program ARSTAN Ver. 44D <<http://www.ideo.columbia.edu/tree-ring-laboratory>>.
- Dai, A., 2011: Characteristics and trends in various forms of the Palmer Drought Severity Index during 1900–2008. *Journal of Geophysical Research*, 116: D12115, <http://dx.doi.org/10.1029/2010JD015541>.
- Dai, A., Trenberth, K. E., and Qian, T., 2004: A global dataset of Palmer Drought Severity Index for 1870–2002: relationship with soil moisture and effects of surface warming. *Journal of Hydrometeorology*, 5: 1117–1130.
- Deng, Y., Gou, X., Gao, L., Zhao, Z., Cao, Z., and Yang, M., 2013: Aridity changes in the eastern Qilian Mountains since AD 1856 reconstructed from tree rings. *Quaternary International*, 283: 78–84.
- Di Filippo, A., Biondi, F., Cufar, K., De Luis, M., Grabner, M., Maugeri, M., Presutti Saba, E., Schirone, B., and Piovesan, G., 2007: Bioclimatology of beech (*Fagus sylvatica* L.) in the Eastern Alps: spatial and altitudinal climatic signals identified through a tree-ring network. *Journal of Biogeography*, 34: 1873–1892.
- Esper, J., Frank, D. C., Wilson, R. J. S., Büntgen, U., and Treydte, K., 2007: Uniform growth trends among central Asian low- and high-elevation juniper tree sites. *Trees—Structure and Function*, 21: 141–150.
- Fang, K., Davi, N., Gou, X., Chen, F., Cook, E., Li, J., and D'Arrigo, R., 2010: Spatial drought reconstructions for central high Asia based on tree rings. *Climate Dynamics*, 35: 941–951.
- Fritts, H. C., 1962: The relation of growth ring widths in American beech and white oak to variations in climate. *Tree-Ring Bulletin*, 25: 2–10.
- Fritts, H. C., 1976. *Tree Rings and Climate*: London and New York: Academic Press.
- Gao, L., Gou, X., Deng, Y., Liu, W., Yang, M., and Zhao, Z., 2013: Climate-growth analysis of Qilian juniper across an altitudinal gradient in the central Qilian Mountains, northwest China. *Trees—Structure and Function*, 27: 379–388.
- Gou, X., Chen, F., Yang, M., Li, J., Peng, J., and Jin, L., 2005: Climatic response of thick leaf spruce (*Picea crassifolia*) tree-ring width at different elevations over Qilian Mountains, northwestern China. *Journal of Arid Environments*, 61: 513–524.
- Gou, X., Chen, F., Yang, M., Gordon, J., Fang, K., Tian, Q., and Zhang, Y., 2008: Asymmetric variability between maximum and minimum temperatures in northeastern Tibetan Plateau: evidence from tree rings. *Science in China Series D: Earth Sciences*, 51: 41–55.
- Holmes, R. L., 1983: Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bulletin*, 43: 69–78.
- Lan, Y., Ding, Y., Shen, Y., Kang, E., and Zhang, J., 2003: Responding of river streamflow to the climate shift in the Hexi Inland Region. *Journal of Glaciology and Geocryology*, 25: 188–192 (in Chinese with English abstract).
- Liang, E. Y., Shao, X. M., and Liu, X. H., 2009a: Annual precipitation variation inferred from tree rings since AD 1770 for the western Qilian Mts., northern Tibetan Plateau. *Tree-Ring Research*, 65: 95–103.
- Liang, E., Eckstein, D., and Shao, X., 2009b: Seasonal cambial activity of relict Chinese pine at the northern limit of its natural distribution in North China—Exploratory results. *IAWA Journal*, 30: 371–378.
- Liang, E., Shao, X., Eckstein, D., and Liu, X., 2010a: Spatial variability of tree growth along a latitudinal transect in the Qilian Mountains, northeastern Tibetan Plateau. *Canadian Journal of Forest Research*, 40: 200–211.
- Liang, E., Wang, Y., Xu, Y., Liu, B., and Shao, X., 2010b: Growth variation in *Abies georgei* var. *smithii* along altitudinal gradients in the Sygera Mountains, southeastern Tibetan Plateau. *Trees—Structure and Function*, 24: 363–373.
- Liu, W., Wang, Q., Wang, X., Zhou, L., Li, F., and Li, Y., 1999: Ecological process of forming “black-soil-type” degraded grassland. *Acta Agrestia Sinica*, 7: 300–307 (in Chinese with English abstract).
- Liu, X., Shao, X., Zhao, L., Qin, D., Chen, T., and Ren, J., 2007: Dendroclimatic temperature record derived from tree-ring width and stable carbon isotope chronologies in the middle Qilian Mountains, China. *Arctic, Antarctic, and Alpine Research*, 39(4): 651–657.
- Liu, Y., Sun, J., Song, H., Cai, Q., Bao, G., and Li, X., 2010: Tree-

- ring hydrologic reconstructions for the Heihe River watershed, western China since AD 1430. *Water Research*, 44: 2781–2792.
- Peng, J., Gou, X., Chen, F., Li, J., Liu, P., and Zhang, Y., 2008: Altitudinal variability of climate-tree growth relationships along a consistent slope of Anyemaqen Mountains, northeastern Tibetan Plateau. *Dendrochronologia*, 26: 87–96.
- Qin, C., Yang, B., Burchardt, I., Hu, X., and Kang, X., 2010: Intensified pluvial conditions during the twentieth century in the inland Heihe River Basin in arid northwestern China over the past millennium. *Global and Planetary Change*, 72: 192–200.
- Rinn, F., 2003: TSAP-Win: Time series analysis and presentation dendrochronology and related applications. Version 0.53 user reference. Heidelberg, Germany.
- Stokes, M. A., and Smiley, T. L., 1968: *An Introduction to Tree-Ring Dating*: Chicago: University of Chicago Press, 73 pp.
- Tian, Q., Gou, X., Zhang, Y., Peng, J., Wang, J., and Chen, T., 2007: Tree-ring based drought reconstruction (AD 1855–2001) for the Qilian Mountains, northwestern China. *Tree-Ring Research*, 63: 27–36.
- Van der Schrier, G., Briffa, K. R., Jones, P. D., and Osborn, T. J., 2006a: Summer moisture variability across Europe. *Journal of Climate*, 19: 2818–2834.
- Van der Schrier, G., Briffa, K. R., Osborn, T. J., and Cook, E. R., 2006b: Summer moisture availability across North America. *Journal of Geophysical Research*, 111: D11102, <http://dx.doi.org/10.1029/2005JD006745>.
- Venugopal, N., and Liangkuwang, M. G., 2007: Cambial activity and annual rhythm of xylem production of elephant apple tree (*Dillenia indica* Linn.) in relation to phenology and climatic factor growing in sub-tropical wet forest of northeast India. *Trees—Structure and Function*, 21: 101–110.
- Wang, T., Ren, H., and Ma, K., 2005: Climatic signals in tree ring of *Picea schrenkiana* along an altitudinal gradient in the central Tianshan Mountains, northwestern China. *Trees—Structure and Function*, 19: 736–742.
- Wells, N., Goddard, S., and Hayes, M. J., 2004: A self-calibrating Palmer Drought Severity Index. *Journal of Climate*, 17: 2335–2351.
- Wigley, T., Briffa, K. R., and Jones, P. D., 1984: On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. *Journal of Climate and Applied Meteorology*, 23: 201–213.
- Yang, B., Qin, C., Bräuning, A., Burchardt, I., and Liu, J., 2010: Rainfall history for the Hexi Corridor in the arid northwest China during the past 620 years derived from tree rings. *International Journal of Climatology*, 31: 1166–1176.

MS accepted May 2013