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Tree rings and climate for the last 680 years in Wulan area of northeastern Qinghai-Tibetan Plateau

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Abstract A 680-year ring-width chronology of *Sabina przewalskii* Kom. was developed for Wulan area of northeastern Qinghai-Tibetan Plateau, China. Response function and correlation analyses showed that spring precipitation (May–June) is the critical limiting factor for tree-ring growth, and temperature in prior November may also play a role in affecting tree-ring growth. Excessive spring precipitation occurred during AD 1380s–1390s, 1410s–1420s, 1520s–1560s and 1938 to present. Dry springs occurred during AD 1430s–1510s, 1640s–1730s and 1780s–1890s most of which generally coincided with cold intervals of the Little Ice Age (LIA) on the plateau, suggesting that the LIA climate on the northeastern Qinghai-Tibetan Plateau might be characterized by three episodes of dry spring and cold autumn. The relatively driest spring and probably coldest autumn occurred in AD 1710s–1720s, 1787–1797, 1815–1824, 1869–1879 and 1891–1895. The extreme drought in AD 1787–1797 might result from little monsoon precipitation due to the failure of Asian monsoon in this period. The tree-ring data produced in this study contribute to the spatial expansion of proxy climate records for the Qinghai-Tibetan Plateau.

1 Introduction

There are only a few weather stations in the vast regions of the Qinghai-Tibetan Plateau, China. The observed climatic records in these stations are usually around 40 years in length. This shortage of data has hindered our ability to understand in detail the long-term climatic variability over large spatial scale. Given the high elevation and sensitivity of this region to

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global climate change (Sun and Zheng 1998), it is of significance to produce long time-series of high-resolution proxy data to better understand past climate variations.

Previous studies of high-resolution proxy climate data on the Qinghai-Tibetan Plateau mainly included records from ice cores and tree rings. The oxygen isotope and ice accumulation data in ice cores from Guliya (Yao et al. 1997) and Dunde (Thompson et al. 1989) showed that fluctuations in temperature and precipitation could be very rapid during the past millennium. Dendrochronological studies were carried out in Linzhi region of southeastern Tibet where the forests were divided into five dendroecological regions of different growth conditions (Wu and Zhan 1991; Bräuning 1994). Summer temperature and summer monsoon history on the southeast Tibetan Plateau were analyzed from data of maximum latewood density (MLD) and stable carbon isotopes in several coniferous species (Bräuning and Mantwill 2004; Helle et al. 2002). In the northeastern Qinghai-Tibetan Plateau, two-millennium long Sabina (*Sabina przewalskii* Kom.) tree-ring chronologies were developed using archaeological wood and living trees (Zhang et al. 2003; Sheppard et al. 2004). These studies indicated that the climate on the Qinghai-Tibetan Plateau is sensitive to global climatic change such as the Medieval Warm Period and the Little Ice Age (Bradley and Jones 1993; Hughes and Diaz 1994), and the patterns of response may change from one area to the other because the climate is shaped by the diverse physiography and monsoonal system (Ye and Gao 1979; Zhang and Crowley 1989; An et al. 2000). Therefore, a better understanding of the spatial patterns in climate variability needs expansion of sample collections over diverse areas on the plateau.

In this paper, we report a dendroclimatological study of *Sabina* trees for Wulan area, northeastern Qinghai-Tibetan Plateau, China. The objectives of the study were to build a multi-century long tree-ring chronology for this area, to identify the relationships between tree-ring growth and climatic variables, and to examine the regional climate variability in the past.

2 Materials and methods

Our study area is located in Wulan (37°02′N, 98°41′E) of northeastern Qinghai-Tibetan Plateau, China (Fig. 1). Mean annual air temperature during the period 1958–2000 is 1.4°C, with a mean maximum of 13.8°C in July and a minimum of −12.9°C in January. Mean annual total precipitation is 194.3 mm, with a maximum monthly sum of 43.4 mm in July. The dominant tree species in this area is *S. przewalskii*, which is sparsely distributed on the mountain slope at an elevation between 3100 m–3800 m a.s.l. The large-diameter *Sabina* trees that live in cold and arid conditions are usually very old and suitable for building long tree-ring chronology and for reconstruction of past climate. The tree-ring samples used in this study were collected from living *Sabina* trees on south-facing mountain slopes. Trees with a large diameter stem were selected for sampling, and one core per tree was extracted at breast height (two cores were extracted from a few exceptionally long-lived trees).

Increment cores were mounted and polished to bring the ring boundaries clearly visible. The ring widths of these samples were measured using a Lintab system (Frank Rinntech Company, Heidelberg, Germany), and the measured series were crossdated by comparing the ring patterns under a microscope and with the aid of the software COFECHA (Holmes 1983). Some increment core samples that contained extremely narrow rings or broken pieces were not crossdatable with the master series and were not used for chronology building. The crossdated ring-width series were detrended and averaged using the software ARSTAN (Cook and Holmes 1996). The biological growth trend in tree-ring series

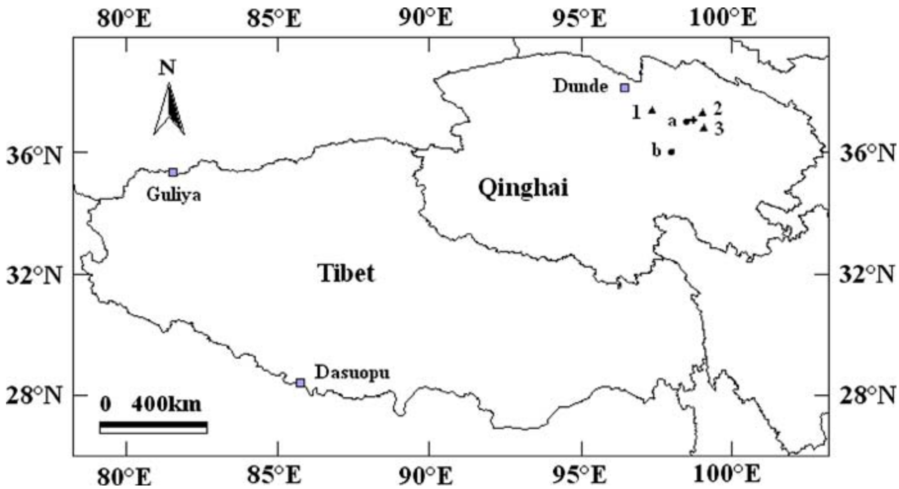

Fig. 1 Map of Qinghai and Tibet in China showing the locations of Wulan (+) for tree-ring chronology, Shenge (•a), Dulan (•b), and Delingha (▲1) for comparing tree-ring chronologies, Dunde (□), Guliya (□) and Dasuopu (□) for comparing ice cores, and the meteorological stations (▲1, Delingha; ▲2, Chaka; and ▲3, Tianjun)

were removed by fitting a curve of either a negative exponential curve, a regression line with a negative slope, or a straight line passing through the mean of the series. This detrending method removed the age-related growth trend and conserved as much as possible the climatic information. The standard ring-width chronology was used for dendroclimatic analysis.

Climate-growth relationships were explored using correlation and response function analyses. The climate data were obtained from regional averages of three nearest weather stations in Delingha (37°22′ N, 97°22′ E), Chaka (36°47′ N, 99°05′ E) and Tianjun (37°18′ N, 99°02′ E) (Fig. 1) for the period AD 1958–2000. Correlations between standard tree-ring chronology and regional temperature and precipitation data were calculated on a monthly basis from August of the prior growth year to September of the current growth year. Correlations were also calculated between the tree-ring chronology and temperature and precipitation over various multimonth seasons and a full-year scale. To avoid the problem of intercorrelation among climatic variables, response function analysis was conducted using the program PRECON (Fritts 1996). The predictor variables for response function analysis were monthly mean temperature and total monthly precipitation in a 14-month period, starting from August of the previous year to September of the growth year. The prior year's growth was also chosen as a predictor variable. Significance test of the response coefficients was conducted using a bootstrap method (Guiot 1991) in which we used 500 replications. Climatic interpretation of the tree-ring chronology was based on the results of climate-growth relationships and on the comparisons with other proxy data in nearby regions.

3 Results

A 680-year long ring-width chronology was developed using 22 good-quality samples (from 22 trees) (Fig. 2). The chronology spanned from AD 1322 to 2001 in which at least five

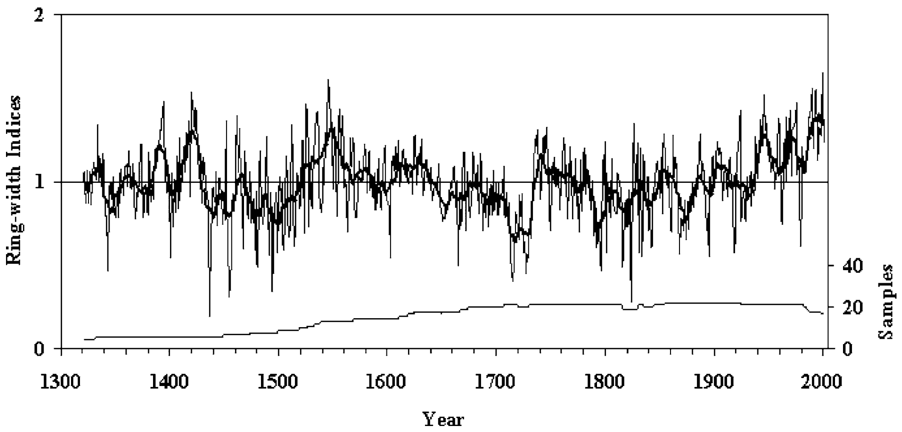

Fig. 2 Standard ring-width chronology and sample size of *Sabina przewalskii* Kom. in Wulan area of northeastern Qinghai-Tibetan Plateau (the thick curve superimposed on the ring-width indices is an 11-year smoothing line)

sample replications were included. The mean value of ring widths was 0.46 mm, indicating that the radial growth of this tree species was slow. The mean sensitivity, which is a measure of relative difference in widths between adjacent rings, was 0.27. The first order auto-correlation was 0.78, suggesting that *Sabina* tree-ring growth in one year influenced its growth in the following year. The average correlation among tree-ring series was 0.58 and the signal to noise ratio was 7.14, indicating that the tree-ring chronology contained common growth-limiting signals, most likely the large-scale climate.

The results of response function analysis showed that the radial growth of *S. przewalskii* was positively correlated with temperature in November of the prior growth year, with total precipitation in March, May and June, and with the growth in the previous year (Fig. 3). The response coefficients for these variables all reached 95% significant level tested by the bootstrap method. Using this response function, 53.4% of the tree-ring variance was explained by climatic variables and 28.1% of the variance was explained by previous year's growth. Correlation analysis showed that the tree-ring indices correlated more strongly with precipitation in June ($r = 0.51, p < 0.01$) than with the temperature in November of the previous year ($r = 0.35, p < 0.05$). The partial correlation coefficient between tree-ring indices and precipitation in June was 0.54, and that between tree-ring indices and temperature in November of the previous year was 0.32. Correlation coefficients between tree-ring indices and total May–June precipitation, and between tree-ring indices and mean September-November temperature of the previous year were 0.46 ($p < 0.01$), and 0.36 ($p < 0.05$), respectively. Given that May–June season is important for setting up the growing condition for *S. przewalskii* trees in this arid region, we consider that total precipitation in May-June is a major limiting factor for tree-ring growth, and temperature in November of the previous year might also play a role in affecting tree-ring growth.

The 680-year ring-width chronology showed that above-average growth (mean ring-width indices greater than 1.20) occurred in the intervals AD 1380s–1390s, 1410s–1420s, 1520s–1560s, and 1938 to present (Fig. 2). The first two periods of above-average growth were short, sustaining only two decades. The years of the widest rings in these two intervals were AD 1393–1394 and 1420–1421 (ring-width indices greater than 1.40). The longest duration of above-average growth occurred in the period AD 1520s–1560s during which wide rings

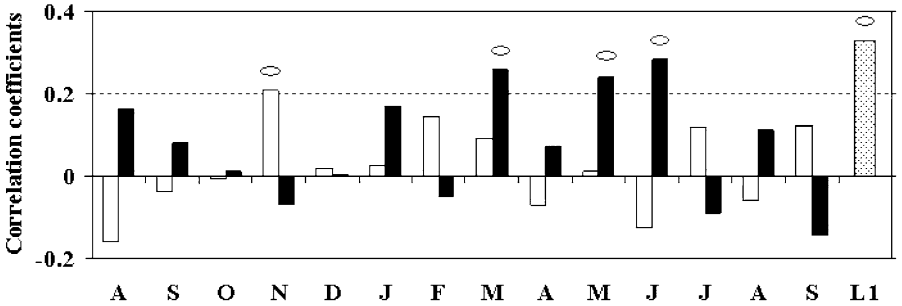

Fig. 3 Response function coefficients. White (Black) bar represents the response of tree-ring indices to mean monthly temperature (total monthly precipitation) from August of the prior growth year to September of the current growth year. Gridding bar represents prior year growth (L1). Ellipse represents significance level at $p < 0.05$

occurred in AD 1524–1525, 1535–1536, 1545–1547 and 1557 (ring-width indices greater than 1.40). In the last period of rapid growth from AD 1938 to present, most of the tree-ring indices were above the long-term mean with the exception of AD 1961–1963 and 1979–1980. Particularly, high values of tree-ring indices appeared in the last two decades.

In contrast, three periods of prolonged growth depression occurred in AD 1430s–1510s, 1640s–1730s and 1780s–1890s, respectively. Superimposed on these centennial-scale growth depressions were annual fluctuations of radial growth in different amplitudes. The most severe and prolonged growth depression occurred in AD 1710s–1720s which fell in the second period of depressed growth. Abrupt growth reduction occurred in different intervals throughout the past 680 years, particularly in AD 1343–1344, 1401, 1403, 1436–1438, 1455–1456, 1480–1481, 1495–1496, 1601–1602, 1672, 1801, 1816–1817, 1824, 1893, 1918–1919 (Fig. 2).

4 Discussion

The radial growth of *S. przewalskii* is sensitive to climatic variation as reported by several studies in nearby areas (Zhang and Wu 1996; Zhang et al. 2003; Sheppard et al. 2004; Shao et al. 2004). Zhang and Wu (1996) studied the dendroclimatology of *S. przewalskii* in Qilian Mountain of northwestern China and found that the growth of ring widths mainly responded to moisture availability in May to July. Zhang et al. (2003) suggested that moisture stress in growing season (May–June) was the major limiting factor to *Sabina* tree-ring growth in Dulan area. Dendroclimatological studies of the same species in Shenge area of the northeastern Qinghai province suggested that the tree-ring chronology was an indicator of precipitation of the entire year from previous July to current June. In this study, the response function analysis showed that precipitation in May-June was an important factor affecting radial growth of *Sabina* trees. It seems that there is no doubt about the importance of precipitation in regulating the tree-ring growth, and the tree-ring chronology is a useful indicator of precipitation variation in the past. The uncertainty is mainly on the question: which season's precipitation is the most critical factor affecting tree-ring growth? We consider May-June precipitation as the main factor affecting tree-ring growth in Wulan area because the growth of trees requires water in various physiological activities (such as photosynthesis, mineral transportation and photosynthates translocation) during its growing season and water availability is limited during this period in the region.

The Wulan chronology showed similar patterns in decadal-scale growth trends with the Dulan chronology (Zhang et al. 2003), which is about 90 km southwest of Wulan. The two chronologies correlated significantly ($r = 0.66$) during the period AD 1322–2000. The episodes of above-average growth in Wulan, AD 1380s–1390s, 1410s–1420s, 1520s–1560s and 1938 to present, were in agreement with the above-average growth in AD 1350s–1420s, 1520s–1570s, and 1940s-present in Dulan. The long periods of below-average growth in Wulan, AD 1430s–1510s and 1640s–1730s, matched with the below-average growth periods AD 1450s–1510s and 1640s–1720s in Dulan. The last two intervals of above-average growth in AD 1520s–1560s and 1938 to present and the intervals of below-average growth in AD 1430s–1510s and 1640s–1730s in Wulan were consistent with the periods of increased growth in 1520–1633 and 1933–2001, and of decreased growth in 1429–1519 and 1634–1741 in Delingha, respectively (Shao et al. 2004). Comparing to the chronologies in Shenge and Dulan in the northeastern Qinghai Province (Sheppard et al. 2004), the Wulan chronology also showed similarities in the growth patterns. The above-average growth in periods AD 1380s–1390s, 1410s–1420s, 1520s–1560s and 1938 to present, and the below-average growth in AD 1430s–1510s and 1640s–1730s in Wulan generally agreed with the periods of high growth in the 1300s, 1500s, and late 1900s, and with the low growth in the late 1400s and around 1700 in Shenge and Dulan. These agreements among different sites suggested that *Sabina* tree-ring growth was subject to large-scale climate variations in the past.

The above-average growth periods AD 1380s–1390s, 1410s–1420s, 1520s–1560s, and 1938 to present in Wulan chronology indicated that abundant spring precipitation and/or warm autumn once prevailed in Wulan region. Correspondingly, three intervals of sustained below-average growth in AD 1430s–1510s, 1640s–1730s and 1780s–1890s reflected a dry-spring and/or cold-autumn climate in this area. The wet-spring and/or warm-autumn periods during AD 1520s–1560s and 1938 to present as recorded in Wulan tree rings coincided with the warm summers around 1550 and the 20th century as indicated by δ^{18}O record from Dunde ice core (Yao et al. 1997). The dry-spring and/or cold-autumn episodes in AD 1430s–1510s and 1780s–1890s as recorded in Wulan tree rings were in agreement with cold summers in intervals AD 1420s–1520s and 1770s–1890s as reflected in Dunde ice core (Yao et al. 1997). The general agreements in these independent proxies suggested that the climate in this region was subject to a large-scale monsoon system (Zhang and Crowley 1989). Differences in the duration of these intervals between Wulan and Dunde might be due to differences in elevation and in seasonal representations of the proxy records, suggesting that the Plateau Mountains and physiography played a role in modifying the monsoon system.

Tree-ring growth shifted from high to low values in AD 1394–1401 and 1420–1436, indicating that the growth conditions could change rapidly from one state to the other probably due to changes in spring precipitation. Correspondingly, the growth release in the interval AD 1401–1420 indicated a change in climate from unfavorable to favorable growth conditions.

The three episodes of dry spring and/or cold autumn in AD 1430s–1510s, 1640s–1730s and 1780s–1890s in Wulan corresponded to the cooling intervals of the Little Ice Age (LIA), which was a period of cold and increased atmospheric circulation from AD ∼1400–1900 (Kreutz et al. 1997). On the plateau, it has been unclear whether the climatic events in the LIA were synchronous over space and accompanied with changes in other climatic parameters, such as seasonal precipitation (Zhang et al. 2003). The occurrence of the LIA in Wulan provided additional evidence to verify the spatiotemperal characteristics of the LIA as revealed in previous studies on the Qinghai-Tibetan Plateau (Yao et al. 1997; Kang et al. 1997; Helle et al. 2002; Sheppard et al. 2004). In Wulan area, the relatively driest spring and/or coldest autumn in the LIA occurred in the intervals AD 1710s–1720s, 1787–1797, 1815–1824, 1869–1879 and 1891–1895. The extreme cold climate centered on AD 1700 in the LIA has been evidenced from ice core data (Yao et al. 1997). The glacier advance in this period is another witness of the LIA (Zheng et al. 1990). Recent reconstruction of annual precipitation by tree rings pointed out that there was a notable dry period from the last half of 17th century to the first half of 18th century in the northeastern Qinghai Province (Sheppard et al. 2004; Shao et al. 2004). These observations supported the tree-ring proxy of dry springs in 1710s–1720s in Wulan. The tree-ring signals of the dry springs and/or cold autumn in AD 1787–1797 coincided well with the Dulan tree-ring records (Zhang et al. 2003), the historical documents of droughts in India during 1790–1796 (Ortlieb 2000), and that of ice core data in Dasuopu of Tibet (Thompson et al. 2000). This unusual period has also been documented in other studies, such as the study of moisture indices from historical documents of China (Gong and Hameed 1991) and tree-ring study from Nepal (Cook et al. 2003). The drought at a large spatial scale might result from little monsoon precipitation dropped in these areas due to the failure of Asian monsoon during this period (Thompson et al. 2000; Bräuning and Mantwill 2004), which has been suggested to be associated with a strong ENSO event of 1790–1793 and a moderate ENSO event of 1794–1797 (Thompson et al. 2000; Wang et al. 2004).

The below average growth in AD 1815–1824 in Wulan area was also reflected by tree rings in Dulan (Zhang et al. 2003), eastern Tibet for the interval 1815–1820 (Bräuning 1994), Kathmandu of eastern Nepal for the interval in 1815–1822 (Cook et al. 2003), and by low $\delta^{18}O$ values in Dasuopu ice core for the interval 1815–1820 (Thompson et al. 2000). These observations implied that the 1815–1824 event had great impacts over large spatial scale. It is interesting to note that the Tambora volcanic eruption occurred in 1815, Indonesia (Rampino and Self 1982), and whether or not the volcanic eruption had an impact on the Tibetan Plateau climate is an open question for further investigation.

The growth minimum in 1891–1895 in Wulan may be associated with a devastating drought in Qinghai, Gansu, and Ningxia of western China in 1890s recorded by historical documents (Yuan 1994). The growth minimum in AD 1961–1963 could be caused by spring drought in 1961–1963, when a 50% decrease in spring precipitation was observed. The low growth in 1979–1980 may be associated with regional snow disaster and subsequent drought as recorded in the study region (Ji et al. 1981). Increased snow cover on the plateau would increase surface albedo and delay snowmelt and, subsequently, reduce the surface heating in spring and lower the thermal contrast for monsoon activity. Besides, it would also shorten the length of growing seasons (Kirdyanov et al. 2003). These observations suggested that the growth minima in Wulan tree-ring chronology contain useful information about past precipitation variations and is helpful for comparisons with other independent proxy data to draw a clearer picture of regional climate changes.

5 Conclusion

The radial growth of *S. przewalskii* trees growing in arid Wulan area of northeastern Qinghai-Tibetan Plateau is sensitive to climate variations. The annual growth rings are firstly limited by spring precipitation (May-June), and secondarily by November temperature, which might play a role in regulating the accumulation of photosynthates for next year's growth. The episodes of above average growth, including AD 1380s–1390s, 1410s–1420s, 1520s–1560s and 1938 to present, indicated that abundant spring precipitation prevailed in these periods on the northeastern Qinghai-Tibetan Plateau. The three periods of sustained below average growth occurred at the intervals AD 1430s–1510s, 1640s–1730s and 1780s–1890s, suggesting that dry springs dominated in these periods. The climate in the LIA on the northeastern

Qinghai-Tibetan Plateau might be characterized by occurrence of three episodes of dry condition in spring and cold condition in autumn. Some relatively severe dry spring occurred in the intervals AD 1710s–1720s, 1787–1797, 1815–1824, 1869–1879 and 1891–1895. The driest springs in AD 1787–1797 could result from little monsoon precipitation dropped in the region due to the failure of Asian monsoon during this period. Tree-ring growth minima as shown in the tree-ring chronology also contained valuable information about past climatic events. With the continued global warming in the 21st century (IPCC 2001), it is important to understand the role of Qinghai-Tibetan Plateau in shaping the Asian monsoon and other global climate systems. To achieve this goal, however, will need more palaeoclimate data in both spatial and temporal coverage on the plateau. The proxy tree-ring data produced in this study are useful for future integration into a large-scale climatic reconstruction for the Qinghai-Tibetan Plateau.

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