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ORIGINAL ARTICLE

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Climatic signals in tree ring of *Picea schrenkiana* along an altitudinal gradient in the central Tianshan Mountains, northwestern China

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Abstract Tree-ring samples of *Picea schrenkiana* (Fisch. et Mey) were studied along an altitudinal gradient in the central Tianshan Mountains, and ring-width chronologies were developed for three sites at different altitudes: low-forest border (1600–1700 m a.s.l.), interior forest (2100–2200 m a.s.l.), and upper treeline (2600–2700 m a.s.l.). Annual ring-width variations were similar among the three sites but variability was greatest at the low-forest border site. The statistical characters of the chronologies showed that mean sensitivity (MS) and standard deviation (SD) decreased with increasing elevation. In other words, the response of tree growth to environmental changes decreased with increasing altitude. To understand the differing response of trees at different elevations to the environmental changes, response function analysis was used to study the relationships between tree-ring widths and mean monthly temperature and total monthly precipitation from 1961 to 2000. The results showed that precipitation was the most important factor limiting tree radial growth in the arid central Tianshan Mountains, precipitation in August of the prior growth year played an important role on tree's radial growth across the entire altitudinal gradient even at the cold, high-elevation treeline site. It is expected that with increasing altitude air temperature decreased and precipitation increased, the importance of precipitation on tree growth decreased, and the response of tree growth to environmental changes decreased, too. This conclusion may be helpful to understand and research the relationship between climatic change and tree growth in arid and semiarid area.

Keywords *Picea schrenkiana,* Tree-ring · Altitude gradient · Dendroclimatology · Treeline

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Introduction

Tree-ring can provide reliable records of past climatic conditions (Fritts 1976). The width of a tree-ring sequence is indicative of the environmental conditions affecting tree growth, and tree-ring chronologies are the most widely used proxy for reconstructing annual variations in climate that extend back several centuries to millennia (Fritts 1976; Bradley and Jones 1992). Trees that occur at the margins of their ecological range are considered to be most sensitive to environmental factors (Kullman 1993), and the strongest relationships between climate and tree radial growth are expected at a species' distributional limits (Fritts et al. 1965; Cullen et al. 2001). Because some woody species are distributed across wide altitudinal ranges and play vital roles in local ecosystems, the dendrochronological and dendroclimatological features of a species at its lower or upper treeline ecotones are of consequent importance for understanding and protecting forests and local ecosystems (Marco and Carlo 2001).

Fritts et al. (1965) introduced the idea of investigating tree-ring growth patterns of a species along ecological gradients and it has been shown that the climatic factors affecting tree radial growth are very different at the upper and lower treeline ecotones. Specifically, the upper forest limit is controlled primarily by low air temperatures whereas the lower forest limit is controlled by precipitation (Fritts et al. 1965; Fritts 1976; LaMarche 1974a; Kienast et al. 1987; Block and Treter 2001). Zhang and Hebda (2004) have also deduced that radial growth of trees in the central coast mountains of British Columbia is subject to conditions associated with changes in elevation.

The Schrenk spruce, *Picea schrenkiana* (Fisch. et Mey), forms the most important forests in the arid land of Xinjiang Uygur Autonomous Region, northwestern China. The Schrenk spruce forest is distributed across a wide elevational range extending from 1500 to 2700 m a.s.l. in the central Tianshan Mountains (Zhang and Tang 1989). To increase our knowledge of what limits the growth of this species at its upper and lower distributional limits, we

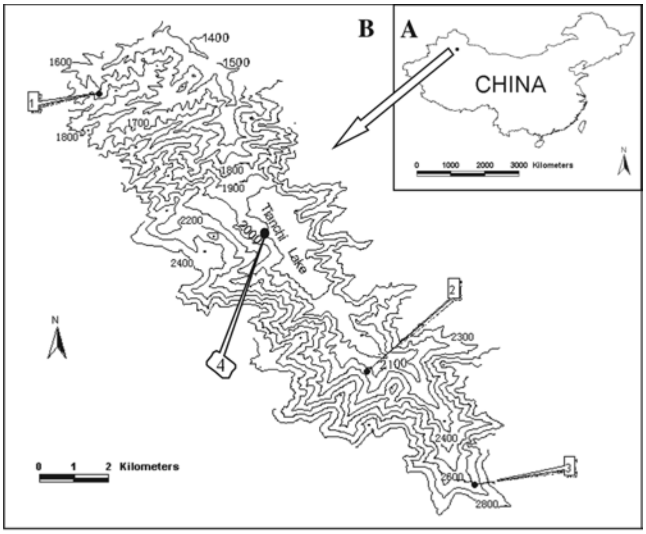

Fig. 1 Location of stands in Tianshan Mountains, northwestern China. **a** Location of study area in China, **b** Scheme of stands in Tianchi forestry center; (1) stand in low forest border (1600–1700 m a.s.l.); (2) stand in interior forest (2100–2200 m a.s.l.); (3) stand in upper treeline (2600–2700 m a.s.l.); (4) Tianchi meteorologic station (1935 m a.s.l.)

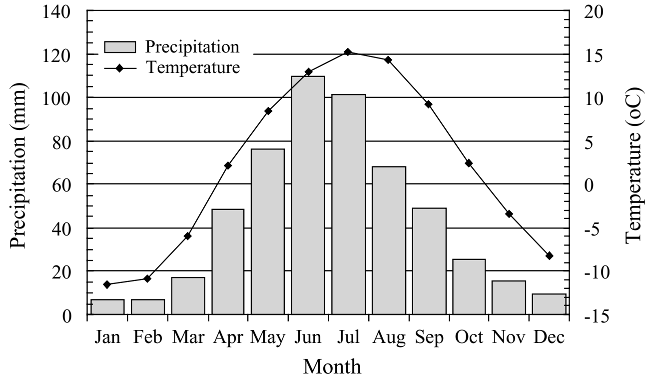

Fig. 2 Mean monthly temperature (°C) and total monthly precipitation (mm) averaged for AD 1961–2000 using records from the Tianchi meteorologic station (1935 m a.s.l.) in the central Tianshan Mountains, northwest China

studied the dendroecological characteristics of Schrenk spruce along an altitudinal gradient. The primary objectives of this study were: (1) to investigate the correlations between tree-ring width and climatic factors at three sites along an altitudinal gradient, the lower forest border, interior forest and upper treeline ecotone; and (2) to compare the similarities and differences in tree radial growth to climatic factors at the three different altitudinal sites.

Materials and methods

Study area

The study was conducted in the Tianchi Nature Reserve in the central Xinjiang Uygur Autonomous Region, northwest China (88°00′–88°20′E, 43°45′–43°59′N). The mean annual precipitation is about 500 mm and the mean annual temperature is 2.04°C (January −11.5°C and July 15.2°C). July is the hottest month with mean temperature 15.2°C and mean precipitation 101 mm (Fig. 1). The mean annual non-frost period is 88.6 days, and the mean relative humidity is 56–64% (climate data were provided by Tianchi meteorologic station, 1935 m a.s.l.). *P. schrenkiana* is the dominant species in the central Tianshan Mountains, forming single-species stands that are distributed from 1500 to 2700 m. There are few anthropogenic disturbances in this area. The soil has been characterized as a mountain gray-brown forest soil (Zhang and Tang 1989), and the soil is deeper than 30 cm in interior forest, and are shallower than 30 cm at the upper treeline and lower forest border (Table 1).

Field sampling

Field work was carried out in the summer of 2001. Three single-species sites were selected at three different elevations in the Tianchi Nature Reserve (Fig. 1b): a low forest border (1600–1700 m a.s.l.), a mid-altitude interior forest (2100–2200 m a.s.l.), and an upper treeline (2600–2700 m a.s.l.). Only trees in arid and infertile environments, for example, in those well-drained slopes with shallow, stony soils, were sampled at each of the three sites for the purpose of maximizing the climate signal registered in the growth rings. Also, only single-stemmed individuals were cored to avoid distortion of the rings due to sprouting. Core samples were extracted at a height of about 1.3 m and 2–3 cores were collected from each tree. The DBH (diameter at breast height) of cored trees were measured, and the numbers of tree (≥2 m) in two stands (20×20 m^2) were counted to calculate the tree density of every different altitudinal zones (Wang et al. 2004). Characteristic of three different altitudinal sites were shown in Table 1.

Table 1 Site description and characteristics of the three selected stands in the central Tianshan Mountains. (a.s.l. = height above sea level, DBH = diameter at breast height, ARI = annual radial increments, SE = standard error)

Site name	Elevation (m a.s.l)	Soil depth (cm)	Canopy coverage (%)	Tree density (ha^{-1})	ARI (mm)	DBH[a] (cm)	Age[b] (yr)
Uarc	2600–2700	<20	43.9±10.2	450±232	0.98±0.03	26.9±2/61.8	141±7/321
Marc	2100–2200	>30	89.5±4.4	1109±119	1.01±0.01	30.8±1.5/76.4	134±9/271
Larc	1600–1700	20–30	50.9±16.5	992±308	0.99±0.02	24±1.8/49.7	66±5/102

*Data are presented in Mean ± SE.

[a,b]: mean values ± SE / maximum.

Data processing

All cores were mounted and then sanded with successively finer grades of sandpaper until annual rings could be easily distinguished. Tree-ring widths of mounted cores were measured to the nearest 0.001 mm using the image analysis system, WinDENDRO 2001b (Université Du Québec À Chicoutimi, Canada). Ring-width series were cross-dated using the software COFECHA (Holmes 1983). Some cores were discarded because of missing rings or rot in the center and only those cores that passed through the center of the tree were used in further analysis. At least, 42 cores from 21 trees were used to form chronologies from the lower forest border, 32 cores from 20 trees were used in the mid-altitude interior forest, and 34 cores from 16 trees were used on the upper treeline ecotone.

Chronology development

Tree age of all samples in the different altitudinal stands were very different, but the maximum tree age at the low forest border was only 102 years old (Wang et al. 2004), which was less than the other two sites. Because it was still a controversial topic that whether climate-growth response was stable across different age classes (Szeicz and MacDonald 1994), we selected the same age core sample as the lower forest border had (≤100 years) to construct chronology sequence (1900–2000) on the different altitudinal sites.

Tree-ring chronologies were constructed using conventional analytical techniques (Fritts 1976; Cook and Kairiukstis 1990). Individual ring-width measurement series were standardized to remove both individual tree and stand-wide variations not related to climatic fluctuations (Fritts 1976; Cook and Kairiukstis 1990; Tardif and Conciatori 2001). In order to remove or minimize long-term and low-frequency trends, all series were standardized using negative exponential curves or straight lines (Szeicz and MacDonald 1994). Residual chronologies that contained only high-frequency variation were developed for the three sites using the software program ARSTAN (Cook and Holmes 1986; Cook and Kairiukstis 1990).

The qualities of all three chronologies were assessed on the basis of the following statistical parameters: standard deviation (SD), mean sensitivity (MS), signal-to-noise ratio (SNR) and expressed population signal (EPS).

Dendroclimatic analysis

Response function analysis was used to quantify relationships between tree-ring chronologies and two climate variables, mean monthly temperature and monthly precipitation (Fritts 1976; Cook and Kairiukstis 1990; Tardif and Conciatori 2001) using PRECON software program version 5.17 (Fritts 1998). Because temperature and precipitation in months that precede the growing season often influence growth (Fritts 1976; Yadav and Singh 2002), temperature and precipitation beginning in June of the previous growth year until August of the current growth year were used to analyze the tree-ring width chronologies from 1900 to 2000.

Results

Site characteristics and chronology qualities at the three-altitudinal stands

The characteristics of the different altitudinal sites were shown in Table 1. Trees growing in the interior forest have the biggest DBH and highest annual ring increment with best environment such as deepest soil. However, low-canopy coverage, shallow soils, stunted-tree growth and narrow annual increment indicated extreme environmental conditions present at upper treeline and low forest border, where growing trees might give better climatic signals.

Following standard procedures, residual chronologies were developed for each of the three sites from 1900 to 2000 (Fig. 3). The tree-ring width chronologies for the three sites showed similar patterns with characteristic narrow rings in the same pointer years such as 1943–1945, 1965, 1974 and 1991. All three chronologies had high MS, SD, SNR, and EPS (Table 2), which indicated all three

Table 2 Summary statistics for tree ring width chronologies from three different altitudinal *Picea schrenkiana* forest sites in the central Tianshan Mountains

Site code	Larc	Marc	Uarc
Altitude (m)	1600–1700	2100–2200	2600–2700
Chronology length	AD 1900–2000	AD 1900–2000	AD 1900–2000
Number of cores/trees	42/21	32/20	34/16
SD (Standard deviation)	0.2660	0.1872	0.1342
MS (Mean sensitivity)	0.3048	0.2101	0.1366
AC1 (Autocorrelation order 1)	−0.0225	−0.0231	0.0777
Mean correlations:			
Among all radii	0.635	0.470	0.339
Between trees	0.627	0.463	0.330
Within trees	0.852	0.708	0.573
SNR (Signal-to-noise ratio)	30.291	14.632	7.887
EPS (express population signal)	0.968	0.936	0.887

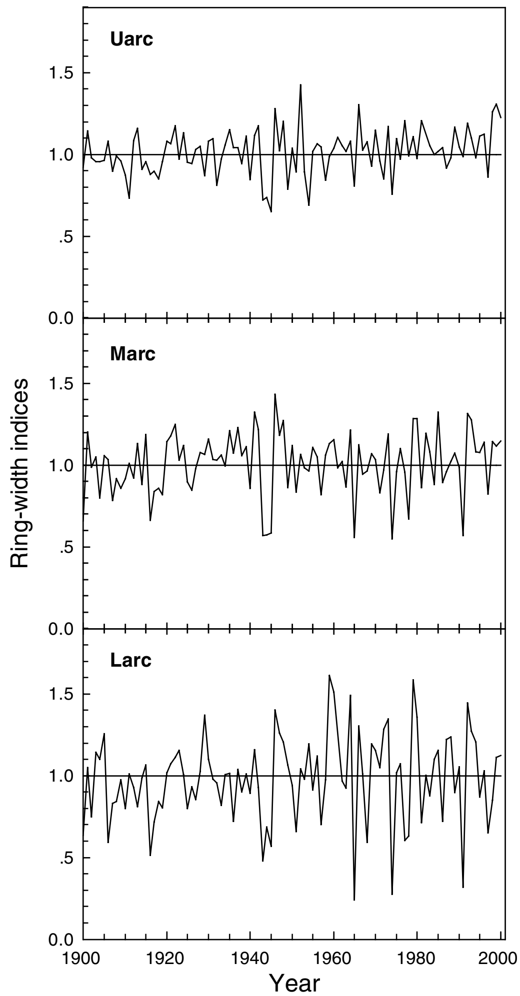

Fig. 3 Tree ring width chronologies for three *Picea schrenkiana* forest sites in the central Tianshan Mountains from 1900–2000. Larc = low forest border site (1600–1700 m a.s.l.); Marc = interior forest (2100–2200 m a.s.l.); Uarc = upper treeline (2600–2700 m a.s.l.)

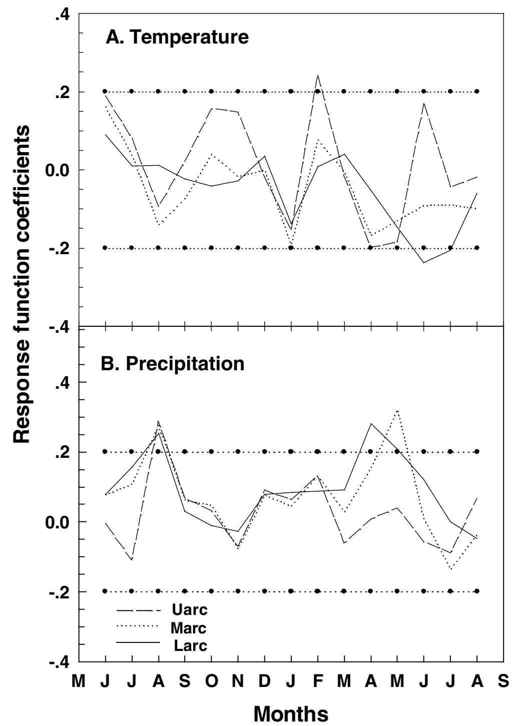

Fig. 4 Response function coefficients between tree ring width chronologies from three *Picea schrenkiana* forest sites in the central Tianshan Mountains and **a** mean monthly temperature and **b** and precipitation from 1961–2000. Larc = low forest border (1600–1700 m a.s.l.); Marc = interior forest (2100–2200 m a.s.l.); Uarc = upper treeline (2600–2700 m a.s.l.). 95% significance levels indicated by horizonal dot-circle line

chronologies having good qualities to study the correlation between tree radial growth and climatic factors.

Response function analysis

Response function analysis of climatic data with tree-ring width data showed different results for the three-altitudinal chronologies (Fig. 4). The lower forest border chronology was positively and significantly correlated with precipitation during August in the year prior to the growth period and precipitation in April and May of the current growth year (Fig. 4b) but negatively correlated with June and July temperatures during the growing season (Fig. 4a). At the mid-altitudinal forest, significant and positive correlations were found between the current May and prior August precipitation (Fig. 4b). On the upper treeline, significant positive correlations were found between tree-ring widths and the prior August precipitation (Fig. 4b) and the current February temperature (Fig. 4a).

Discussion

Qualities of different altitudinal chronologies

It was found that relatively narrow tree rings were produced in the same years at all three altitudinal sites, but the average ring-width of those pointer years were decreased from the upper to lower forest border (Fig. 3). For example, the average ring-width of the pointer year 1965 from the three chronologies Uarc, Marc and Larc were 0.807, 0.69 and 0.239, respectively, which were decreased with decreasing altitude (Fig. 3). On the other hand, the quality of the three chronologies decreased with increasing altitude, and the chronology Larc with the highest quality and sensitivity was also obtained from the extreme site near the lower forest border (Table 2). In other words, the sensitivity and the consistency of the tree's response to the environment increased with decreasing altitude, and the response of tree growth to environmental changes was strongest at low forest border with best statistical character such as MS, SD, SNR and EPS (Table 2).

Similar findings were described in earlier studies by Fritts et al. (1965), LaMarche (1974a) and Kienast et al. (1987). The increased variability with decreasing altitude may be the result of increasing climatic control over tree physiological processes that ultimately influence tree growth (Fritts et al. 1965).

Climate effects on ring widths at different altitudes

Response function analysis reflected the strength of the linear relationship between climatic data and tree ring widths (Fritts 1976). Our results showed that relationships between tree radial growth and climatic change were very different in the three different altitudinal forest zone. At the low forest border, precipitation during April and May had a decisive effect at the lower-elevation sites because it can enhance early wood formation and thus strongly influence total annual ring width (LaMarche 1974a; Kienast et al. 1987). However, high temperatures during June and July often cause soil moisture drought (D'Arrigo et al. 2001), such a water deficit were more detrimental to tree growth at their lower distribution limit (LaMarche 1974a; Takahashi et al. 2003). Therefore, radial growth of *Picea schrenkiana* at their lower distribution limit was mainly affected by drought stress.

In the mid-altitude interior forest, significant positive correlations were found between tree growth and precipitation during current May and prior August. With increasing altitude, it was moister and colder in interior forest than in the low forest border. The soil moisture, not temperature, was still the most important factor influencing tree radial growth in interior forest (Shao and Wu 1994).

At the upper treeline ecotone, precipitation of prior August and temperatures of current February exerted significant positive effect on tree radial growth. With high-soil moisture on the upper treeline (Wang et al. 2004), tree radial growth was influenced more by the amount of storage compounds rather than by the current soil moisture regime (Fritts et al. 1965). It was inferred that most plant growth occurred during June–July in response to the moisture stored from rain and snow melt since the previous August (Sauchyn and Geo 2000). It was also deduced that warmer winter (November–February) temperatures on upper treeline might reduce the loss of carbohydrates stored from the previous growing season and increase carbohydrate stores for greater growth in the following summer (Cullen et al. 2001). Yuan and Li (1999) had also concluded that the radial growth of *P. schrenkiana* was positively correlated with warmer winter temperatures in high-elevation forests of the central Tianshan Mountains. Our results were consistent with a growing number of studies that tree growth near alpine tree limits was negatively affected by low winter temperatures (Jacoby and D'Arrige 1989; Grace and Norton 1990), because winter cold stress may induce some kind of permanent physiological shock to foliage and thus inhibit growth in the following season (Kullman 1990; Oleksyn et al. 1998).

Comparison among the different altitude chronologies

Response function analysis also showed that tree-ring-width indices of the three different altitudes were all positively correlated with August precipitation in the prior year. This conclusion was very different from that of previous studies that tree-ring widths were significantly and positively correlated with temperature at upper cold treeline, whereas significantly correlated with precipitation at lower arid forest limit (LaMarche and Stockton 1974; Kienast et al. 1987).

On the arid Tianshan Mountains, *Picea schrenkiana* is one species of hygrophilous trees (Zhang and Tang 1989), precipitation from July to February exerts an important role on *P. schrenkiana* radial growth (Yuan et al. 2001). However, August has the lowest amount precipitation but higher temperature compared with June and July (Fig. 2). High temperatures coupled with low precipitation cause drought stress, stomatal closure and reduced carbon assimilation (Cienciala et al. 1994). High precipitations during the hot August most likely enhance photosynthetic rates and the production of sugars, the sugars are stored in branches and needles over the winter (Takahashi et al. 2003) resulting in more stored food reserves for tree growth in the following summer (LaMarche 1974a). Thus, high precipitation in the prior August had a positive effect on tree growth at both the upper or lower limits on the central Tianshan Mountains.

However, there were some important differences among the three chronologies and their correlations with climatic factors. With ascending elevation, precipitation (Lin 1995) and soil moisture (Wang et al. 2004) increased, whereas temperature decreased. Precipitation in growing season was less important factor in controlling tree-ring growth in high-elevation zones than it did in low-elevation sites on the central Tianshan Mountains.

At the low-elevation forest borders, temperature during June and July was negatively correlated with ring widths. A cool, moist growing season can result in the formation of wide tree rings at the low forest border (LaMarche 1974a) because evapotranspiration losses were smaller and water stress reduced (Kienast et al. 1987). With increasing altitude, temperature decreased. Temperature in growth season was less important in controlling tree radial growth as no significant correlation between temperature and ring width were found in the interior forest. At upper treeline, tree radial growth only significantly and positively correlated with February temperatures but did not significantly correlated with summer temperature. This result was different from some previous studies that high temperature in summer could form wider tree ring (Jacoby et al. 1985; Esper et al. 2003) and low summer temperature limited ring width on the high-altitudinal cold treeline (Splechtna et al. 2000). At higher treeline of central Tianshan Mountains, temperature of the hottest month July is less than 15°C (Fig. 2). It was probable that the accumulated temperature, rather than monthly temperature during the current growth season, exerted the most important influence on tree radial growth at the high, cold treeline. On the other hand, trees remain dormant during winter (November–February), warmer February most likely activate trees activity and speed up snowpack melt with a subsequent positive effect on soil moisture in early spring (D'Arrigo et al. 2001). Consequently, annual radial increment was further controlled by precipitation and temperature prior to the growing season with their indirect affect on the annual ring-width formation at the upper treeline of the central Tianshan Mountains.

Conclusions

In summary, soil moisture stress appears to be the most important factor limiting tree growth in the arid central Tianshan Mountains even at the cold upper treeline. Our results were similar to the findings by LaMarche (1974b) and Hughes and Funkhouser (2003), which showed that high-frequency (one to several years) variation in tree-ring widths were positively related to precipitation even at the upper forest border. With decreasing altitude, average temperature increased and the importance of precipitation increased, and trees showed a strong 'drought-sensitive' climatic response at the lower forest site. Precipitation can affect tree growth over long time periods, and prior August precipitation played an important role on tree radial growth across the elevational gradient in the central Tianshan Mountains. The sensitivity and the consistency of the tree's response to the environment decreased with increasing altitude, and the response of tree growth to environmental changes was weakest at high treeline. This conclusion may be helpful to understand the relationship between climatic change and tree growth in arid and semi-arid area but need receiving more attention and research to explain and testify its validity in the future.

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