Growth responses of subalpine fir (*Abies fargesii*) to climate variability in the Qinling Mountain, China

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Abstract

Dendroecological techniques have been employed to investigate the relationship between subalpine fir (*Abies fargesii*) growth and climatic variability throughout its elevational range on both south and north aspects in the Qinling Mountain of Shaanxi Province, China. Correlation analyses indicate that early spring and summer temperatures are the principal factors limiting its growth in the low- and middle-elevation distributional areas. In the high-elevation areas, it is the summer precipitation that affects *A. fargesii* radial growth. The previous year August and November temperatures show positive correlation with the radial growth in the low- and middle-elevation distributional areas of the south aspect, and in the high-elevation areas, precipitation in previous November has significantly negative influences on the radial growth. The previous year's temperature and precipitation have no significant effects on the radial growth of the fir trees in the north aspect. Thus, the growth of the subalpine *A. fargesii* responds differently to climatic conditions along the elevational gradient and in different aspects.
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Keywords: Growth response; Subalpine fir; Radial growth; The Qinling Mountain

1. Introduction

Dendroecological techniques have been recognized as a useful tool for exploring the relationships between environmental factors such as climatic variables and radial growth of trees (Fritts and Swetnam, 1989; Rigling et al., 2001; Copenheaver and Abrams, 2003; Andreassen et al., 2006). In the subalpine environment, the growth conditions of tree species vary greatly with altitude, tree-rings can provide climatically sensitive records demonstrating different relationships with the vertical changes in climatic conditions (Kienast et al., 1987; Villalba et al., 1997; Yoo and Wright, 2000). Ecotones (i.e., transitional zone between adjacent communities; Odum, 1971) along altitudinal gradient in subalpine environment, such as the lower and upper distributional limits of tree species, have been identified as particularly vulnerable areas that may be the first to reflect changes in local biophysical characteristics (Villalba et al., 1994; Liu et al., 2001a; Takahashi et al., 2003).

Abies fargesii is a subalpine tree species widely distributing in the Qinling Mountain and Daba Mountain of China. It occurs over a wide elevational range and dominates the forests above 2400 m a.s.l. in the Qinling Mountain. Previous studies have utilized dendrochronological techniques to reconstruct past climate conditions (Hughes et al., 1994; Wu and Shao, 1994; Dai et al., 2003; Liu and Shao, 2003). As the region is located in the transitional zone between two macroclimatic regimes (i.e., subtropical and warm-temperate zones) in China, understanding the growth responses of *A. fargesii* along elevation gradient is of great importance for the sustainable forestry in the context of climatic change. In this study, we sampled *A. fargesii* along its distributional range in elevation and in both south and north aspects in the Qinling Mountain, and used dendrochronological techniques (1) to examine the variation in tree-ring growth of *A. fargesii* along the elevational gradient and in south and north aspects; (2) to identify the climatic factors that are responsible for the variation in its radial growth.

2. Methods

2.1. Study area

This study was conducted in the Foping and Zhouzhi National Nature Reserves, located, respectively, in the south and north
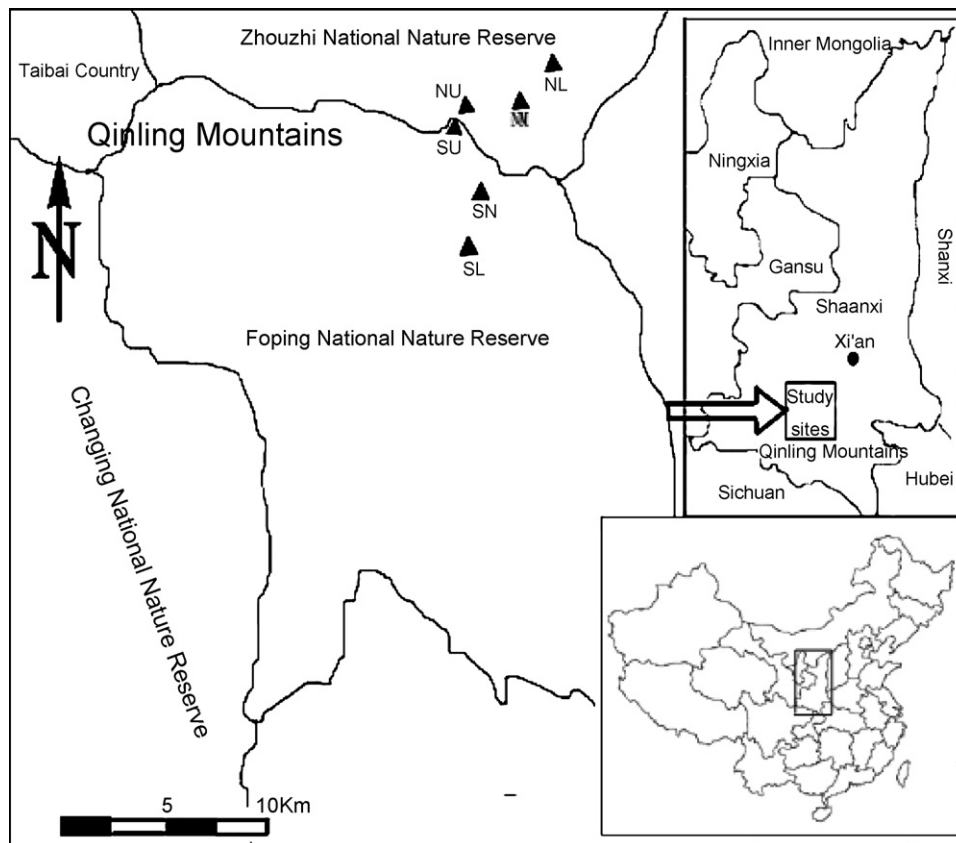
Fig. 1. Locations of the six sampling sites (▲) in the Qinling Mountain of Shaanxi province, China. NL, lower distribution limit in the north aspect; NM, middle distribution zone in the north aspect; NU, upper distribution limit in the north aspect; SL, lower distribution limit in the south aspect; SM, middle distribution zone in the south aspect; SU, upper distribution limit in the south aspect.

aspect of the Qinling Mountain of Shaanxi Province, China (Fig. 1). Elevation in the study area ranges from 980 to 2838 m. The south aspect is of subtropical characteristics with wet summers and warm winters, while the north belongs to warm-temperate zone with relatively dry summers and cold winters (Chen, 1983). Annual precipitation ranges from 950 to 1200 mm, most of which falls between July and September. Snow cover usually lasts five or more months (from November to March), and annual mean temperature ranges from 6 to 11 °C below 2000 m and from 1 to 6 °C above 2000 m a.s.l. (Yue et al., 1999).

Vegetation of the study area comprises of deciduous broad-leaved forests, mixed conifer and deciduous forests, conifer forests and subalpine meadow along the elevational gradient. *Fargesia spathacea* and *Bashania fargesii* are common understory species. Conifers dominated by subalpine fir (*A. fargesii*) occupy the area above 2300 m in elevation, and *A. fargesii* usually develops into mixed forests with birch (*Betula albo-sinensis* var. *septentrionalis*) or forms pure conifer forests above 2300 m. Between the elevation of 1800–2300 m are the mixed conifer and deciduous forests. The deciduous broad-leaved forests grow between the elevation of 980–1800 m. Patchy subalpine meadow occurs above 2600 m a.s.l. (Yue et al., 1999).

2.2. Data collection

In the sampling areas of the Foping and Zhouzhi National Nature Reserves (Fig. 1), subalpine fir (*A. fargesii*) is a

dominant or codominant species along the elevational gradient. We have chosen three sites each in the north and south aspects, spanning the elevational range of the subalpine fir: one in the transitional zone between conifer forest and subalpine meadow in the higher elevation, one in the mixed conifer and deciduous forest in the lower elevation, and one in the middle elevation area where the subalpine fir (*A. fargesii*) is the dominant species (Table 1). The vertical distance between the upper and lower sites is 320 m in the south aspect and 400 m in the north aspect. The sampling sites are located in the relatively flat areas with fine to medium-textured substrates.

In each site, a large sample plot ($\geq$100 m $\times$ 20 m) was established, orientating parallel to the isoline to minimize climate variability within each sampling site. All the large and presumably old fir trees within the plots were selected for increment core sampling at breast height (1.3 m above the ground). One or two increment cores per tree were extracted in the direction parallel to the slope contour using increment borers. For a few trees with broken increment core, one additional core from the opposite side was extracted. In total, 223 increment cores were collected from 192 living subalpine fir trees.

2.3. Chronology development

The increment cores were air-dried in the laboratory and mounted on grooved wooden boards. Mounted increment cores

Table 1
Characteristics of the sampling sites in the Qinling Mountain of Shaanxi province, China

Study area	Sampling location	Sampling site code	Elevation (m)	Mean annual temperature (°C)	Annual precipitation (mm)	Slope (%)
North aspect	Lower limit	NL	2360	6.4	1018.1	40
	Middle elevation	NM	2540	5.2	1047.5	26
	Upper limit	NU	2760	3.7	1083.2	30
South aspect	Lower limit	SL	2350	6.5	1016.8	15
	Middle elevation	SM	2480	5.9	1032.6	20
	Upper limit	SU	2670	4.3	1070.5	35

Mean annual temperature and annual precipitation were calculated from the Foping meteorological station (1087 m a.s.l, approximately 28 km southeast of the study area) using the MTCLIM program (Running et al., 1987; Thornton et al., 1997).

were sanded with progressively finer grades of sandpaper to produce a flat and polished surface on which tree-ring boundaries were clearly visible. The ring widths were measured to the nearest 0.01 mm with the Windendro image-analysis system (Regent instruments Inc., Quebec, Canada). The COFECHA computer program (Holmes, 1983, 1994) was used to test the measured tree-ring series for possible dating or measurement errors. All cores with potential errors were rechecked and corrected if possible; otherwise, they were eliminated from further analysis. Additionally, series that had low correlation with the master dating series (mean of all series) were also excluded. As a result, increment cores from 152 trees were selected (cores from 40 trees were eliminated) for the construction of tree-ring chronologies (Table 2).

Ring-width chronologies were derived for each site using ARSTAN (Cook, 1985; Cook and Holmes, 1996). A negative exponential curve was used to detrend the tree-ring series to remove the biological growth trend related to the tree's age. The tree-ring index series were detrended for a second time to remove low-frequency growth trends by fitting a cubic spline curve with a 50% frequency-response cutoff at 60 years. Site chronologies were then developed by averaging ring-width indices by year across different samples for each site, using a biweight robust mean to further remove the random signals related to local disturbances (Cook et al., 1990). The resulting standard tree-ring chronology reflected mainly the variations in climate. At least 10 sample replications were used to determine the tree-ring width chronologies in each year.

Site chronologies were characterized using following statistics. Mean sensitivity indicates the year-to-year variability in tree-ring records and its values range from 0 (indicating no

yearly changes in ring width) to 2 (indicating a missing ring), and large values imply that the ring-width series have dendroclimatological utility (Fritts, 1991). Standard deviation is an indicator of the interannual variation in tree-ring growth of a chronology. Mean series correlation is calculated as the mean correlation coefficient between individual ring-width series and the site chronology. Large values suggest that the trees are responding in a similar manner to external influences and likely contain a strong climate signal. Autocorrelation is a measure of the association between growth in the previous year and that in the current year, with large values indicating that a significant portion of the observed ring-width is a function of the preceding year's growth rather than exogenous factors. Signal/noise ratio is a measure of the strength of the common signals relative to the uncommon signals of noise.

2.4. Climatic data

The climate data (1957–2004) from the Foping meteorological station (1087 m a.s.l, approximately 28 km southeast of the study area) were utilized in the study. Considering the difference in climate between the station and the sampling sites, the Mountain Climate Simulator (MTCLIM) (Version 4.3; School of Forestry, University of Montana) was employed to derive climate variables for the sampling sites. The MTCLIM is a program that uses daily observations from one location to estimate the temperature, precipitation, radiation, and humidity for another, in particular in mountainous terrains. A number of studies have validated its reliability by comparing predictions with data from actual climate stations (Running et al., 1987; Hungerford et al., 1989; Glassy and Running, 1994; Thornton

Table 2
Dendrochronological characteristics of *Abies fargesii* ring-width chronologies in the Qinling Mountain of Shaanxi province, China

Site code	Chronology (years)	No. of trees	Mean sensitivity	Mean series correlation	Signal/noise ratio	Mean ring-width (mm)	S.D.	First-order autocorrelation
NL	1840–2004(165)	27	0.235	0.357	10.616	1.49	0.187	0.518
NM	1836–2004(169)	34	0.242	0.516	5.159	1.10	0.202	0.443
NU	1811–2004(194)	17	0.256	0.545	6.261	0.73	0.249	0.559
SL	1837–2004(168)	23	0.141	0.345	3.129	1.82	0.193	0.498
SM	1845–2004(160)	31	0.243	0.505	2.684	1.10	0.236	0.430
SU	1848–2004(157)	20	0.130	0.253	7.147	0.87	0.145	0.576

Note: NL, lower distribution limit in north aspect; NM, middle distribution zone in north aspect; NU, upper distribution limit in north aspect; SL, lower distribution limit in south aspect; SM, middle distribution zone in south aspect; SU, upper distribution limit in south aspect.

et al., 1997). It "adjusts" temperature, vapor pressure, and solar radiation in a "base" location (e.g. meteorological station) to a specific site based on latitude, elevation, and mean yearly precipitation. Input data from the meteorological stations include daily observations of maximum and minimum temperature, and daily total precipitation. The output information includes daily mean temperature and daily total precipitation, and monthly mean temperature and total monthly precipitation were then derived.

2.5. Responses to climatic conditions

Standard correlation function analysis was applied to determine correlations between the derived chronologies and the climatic variables (Fritts, 1976). The analyses were performed with the help of the Dendroclim2002 program (Biondi and Waikul, 2004), using the derived mean monthly temperature and total monthly precipitation. The statistical association between ring-width indices and each climate variable derived from program MTCLIM was examined over the time period of 1957–2004. As radial growth may be affected not only by the climatic conditions of the current growing season but also by those of the previous growing season (Fritts, 1976; Lara et al., 2001; Zhang and Hebda, 2004), both the previous and the current growing seasons were included in this study. Correlation analyses between ring widths and climatic variables were performed for 15 months in total, starting in August of the previous growing season, and ending in October of the current growing season.

3. Results

3.1. Tree-ring width chronologies

Ring-width chronologies for A. fargesii and the statistics are presented in Figs. 2 and 3 and Table 2. The mean sensitivity, standard deviation and mean series correlation tend to increase
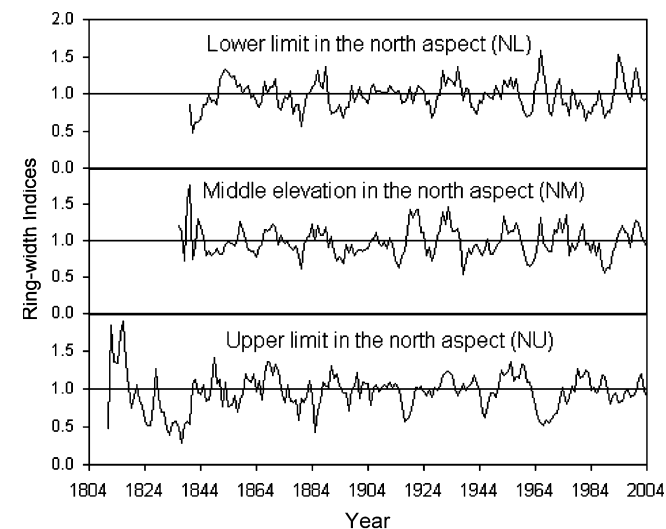

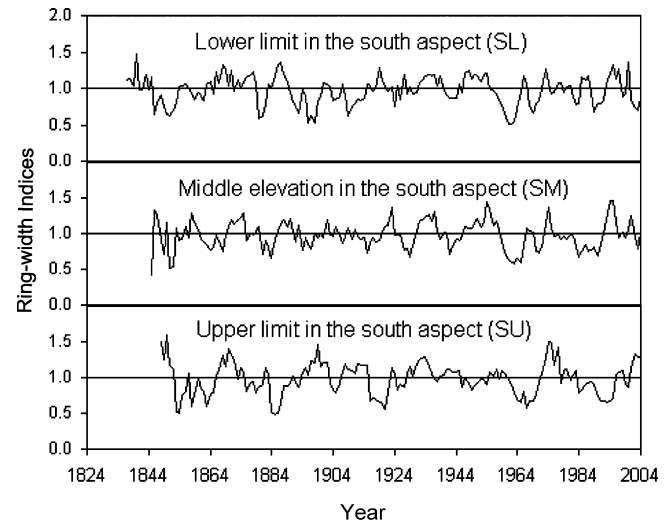Fig. 2. Ring-width chronologies of A. fargesii in the north aspect of the Qinling Mountain.

Fig. 3. Ring-width chronologies of A. fargesii in the south aspect of the Qinling Mountain.

along the elevational gradient in the north aspect, while there are no consistent trends in the south aspect (Table 2). The largest mean sensitivity and standard deviations occur in the upper limit (NU, 0.256, 0.249) and the middle distribution zone (SM, 0.243, 0.236) in the respective north and south aspects. The variations of the mean series correlation in both north aspect (0.357–0.545) and south aspect (0.253–0.505) are comparable. The mean ring-widths in both aspects display the consistent variation patterns, i.e., reduction with the increase in elevation. The north sites generally have larger signal-to-noise ratio than the south sites. The first-order autocorrelations of chronologies, as measures of the influence of previous year's growth on the growth in the current year, range from 0.430 to 0.576 with the largest values in the NU site (0.559) in the north aspect and the SU site (0.576) in the south aspect.

3.2. Response to climatic conditions

Temperatures in the early spring and summer of the current year show positively correlations with ring-width indices in the lower and middle distribution zones (site NL and NM); while temperature in July of the current year is negatively correlated with ring-width indices in the upper distribution limit (site NU) (Fig. 4). Precipitation shows no significant correlation with the tree-ring width indices in the lower and middle distribution zones (site NL and NM), but it is positively correlated with precipitation in June and July of the current year in the upper distribution limit in the north aspect (Fig. 4).

In the south aspect, temperatures in previous August and in current April, May and July demonstrate significant positive correlations with the site chronology in the lower elevation area (site SL), and temperatures in the previous November and in the current March, April and July show significant positive correlations with the site chronology in site SM (Fig. 5). Meanwhile, temperatures are not significantly correlated with ring-width indices in the upper distribution limit. Precipitation illustrates no significant correlations with tree-ring width
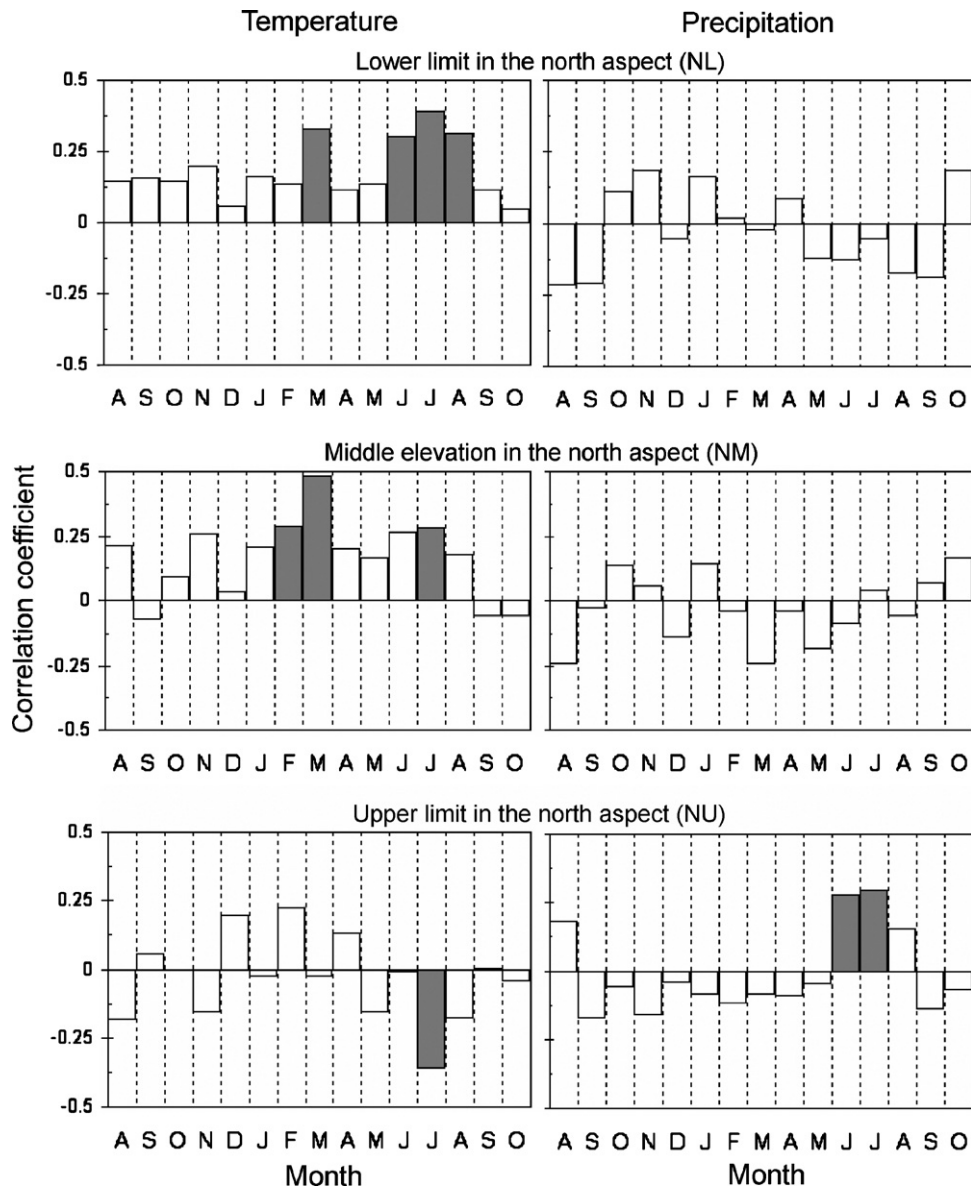
Fig. 4. Correlation coefficients between site chronologies and monthly climatic variables (temperature and precipitation) in the north aspect of the Qinling Mountain. Solid bars indicate significant correlations at $P \leq 0.05$ level.

indices in the lower and middle elevations (site SL and SM), whereas precipitation in November of the previous year and in July of the current year shows significantly negative and positive correlations with ring-width indices in the upper elevation (site SU), respectively (Fig. 5).

4. Discussion

Patterns of tree growth and the relationships between growth and climate conditions vary greatly among regions, elevations and over time (Yoo and Wright, 2000). This study conducted in the Qinling Mountain demonstrates the variability in growth pattern along the elevational gradient and that in different aspects on a relatively small geographical region. The statistics used to characterize these chronologies (Table 2) indicate that the chronologies are of the similar quality to the *A. fargesii*

chronologies developed from sites on the eastern side of the Qinling Mountain (Liu et al., 2001b; Liu and Shao, 2003).

The largest values of mean sensitivity and standard deviation for the site NU in the north aspect and the site SM in the south aspect indicate the strongest climatic signal in those sites (Cook et al., 1990). The values of mean serial correlation and signal/noise ratio suggest that the individual trees contain sufficient common environmental signal in their annual growth rings (Fritts and Shatz, 1975). The relatively low mean series correlations for three of the six sites (0.357, 0.345 and 0.253 for site NL, SL and SU, respectively) imply weak uniformity of trees' response to environmental conditions. Perhaps climate conditions are much favorable and competition among individual trees may have affected radial growth of trees in the lower elevation areas (i.e., NL, SL), while in the forest-meadow ecotone (i.e., SU), complex topography could
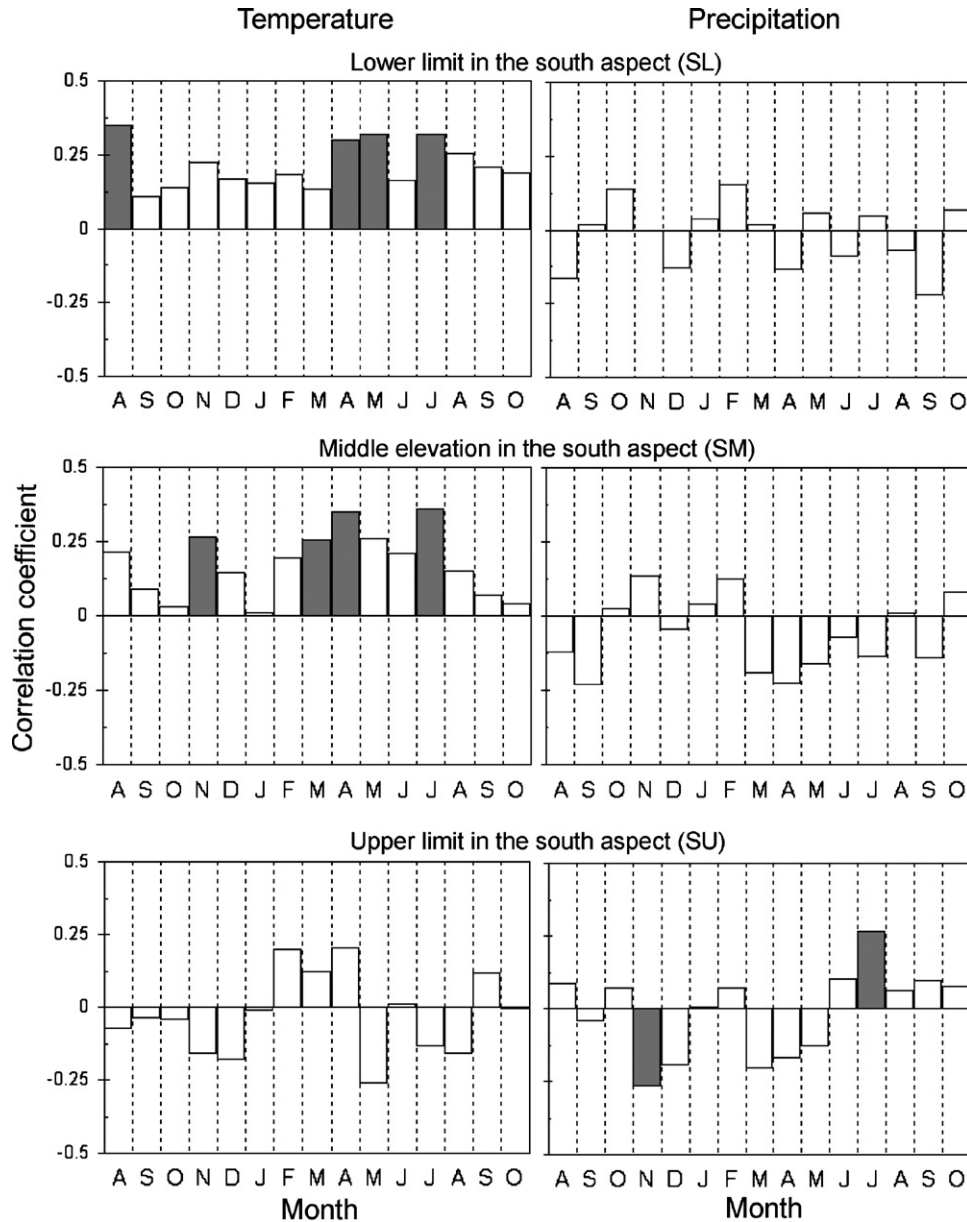
Fig. 5. Correlation coefficients between site chronologies and monthly climatic variables (temperature and precipitation) in the south aspect of the Qinling Mountain. Solid bars indicate significant correlations at $P \leq 0.05$ level.

potentially induce greater differences in microenvironment, thereby reducing the consistency of trees' response to environmental changes and resulting in the relatively low mean series correlations (Peterson et al., 2002). The first-order autocorrelations range from 0.430 to 0.576, indicating that the chronologies contain low-frequency variance induced by climatic factor or/and lag effects of tree physiology, such as needle retention and nutrient reserves for growth in the following year (Fritts, 1976).

Radial growth of subalpine fir declines with increasing elevation in this study. At the low- and middle-elevation distribution areas, temperatures in the early spring (February–April) and in the summer (July in particular) of the current growing season show significantly positive correlations with the *A. fargesii* ring-width growth, while precipitation shows no

such significant correlation (Figs. 4 and 5). The result is consistent with the previous studies indicating that temperature, especially in early spring, is the main climatic factor controlling tree radial growth in the subalpine environment (Hughes et al., 1994; Wu and Shao, 1994; Liu et al., 2001b; Dai et al., 2003; Liu and Shao, 2003). The warm temperatures in the early growing season may reduce wintertime's dormancy level (Waring and Franklin, 1979), raise soil and leaf temperature and promote rapid root and shoot growth (Peterson et al., 2002), induce earlier snow melt thereby lengthening growing season (Case and Peterson, 2005), and result in early initiation of cambial activity and increase supply of photosynthates (Splechtna et al., 2000). As a result, tree will have produced more photosynthates in the warmer years, and wider rings will be produced.

The growth responses of *A. fargesii* to climatic variables in the high-elevation sites differ greatly from those in the low- and middle-elevation sites (Figs. 4 and 5). In the high-elevation sites, it shows positive association with precipitation in the current summer, but temperatures display either no significant correlation in the south aspect or negative correlation with ring-width growth in the north aspect (Figs. 4 and 5). The results are inconsistent with previous studies demonstrating that temperature especially in early spring was the main climatic factor limiting tree radial growth (Hughes et al., 1994; Wu and Shao, 1994; Liu et al., 2001b; Dai et al., 2003; Liu and Shao, 2003). In the study area, *F. spathacea* about 3 m in height is a common understory species whose coverage almost amounts to 100% in the low- and middle-elevations, increasing the water-holding capacity. Despite the larger amount of rain in the upper limits, the water storage is low due to the absence of the cover of *F. spathacea* as well as the thin soil layer. Thus, radial growth of *A. fargesii* is influenced more by precipitation in the upper limits than in the lower- and middle-elevations. As for the negative association of current July temperature with tree radial growth in the north aspect (site NU) (Fig. 4), the possibility is that high temperature in summer could enhance evapotranspiration and decrease the amount of soil water available, consequently reduce radial growth (Lara et al., 2001).

The radial growth patterns reflect the differences in tree's responses to temperature and precipitation variations between the south and north aspects. Climatic variables of the preceding year have no significant effects on *A. fargesii* radial growth of the current year in the north aspect (Fig. 4). In the south aspect, however, previous August temperature in the low-elevation site (site SL) and previous November temperature in the middle-elevation site (site SM) have positive impact on the ring-width growth of the current year, and precipitation in previous November in the high-elevation site (site SU) exerts a negative influence on *A. fargesii* growth of the current year (Fig. 5). The difference in the south and north aspects is attributable to the climatic conditions in the Qinling Mountain. The south aspect is wetter and warmer than the north aspect (Chen, 1983; Liu and Shao, 2003). Higher temperature in the previous growing season in the south aspect may increase the carbohydrate production of subalpine conifers (Gedalof and Smith, 2001). The negative association with November precipitation in previous year in the high-elevation site of the south aspect may be a response to mechanical damage from freezing rain or snows, resulting in the decreased radial growth in the following season due to the lost of photosynthetic resources and a greater need for carbohydrate allocation in the damaged shoots (Gedalof and Smith, 2001).

Although the growth of the subalpine tree has been generally considered more sensitive to temperature variation than precipitation (Lara et al., 2001), our results show that temperature is the major factor affecting the radial growth of *A. fargesii* in the lower and middle elevation areas, yet in the high-elevation sites it is precipitation controlling its growth. In general, the results are consistent with the previous report (Villalba et al., 1994; Peterson et al., 2002; Mäkinen et al., 2002), showing that spring and summer temperature and summer precipitation are the primary climatic factors associated with the annual growth variability of subalpine fir in the continental climate regions.

5. Conclusion

Subalpine fir (*A. fargesii*) shows different radial growth patterns in response to the climatic variability along the elevational gradient and between the south and north aspects in the Qinling Mountain. In the lower and middle elevations, temperature in the early spring and summer of the current year shows positive correlations with the radial growth, while precipitation in the current summer is the principal factor affecting ring-width growth in the higher elevation areas. Climatic conditions of the previous growing season could influence ring-width growth of the subalpine fir in the south aspect, but the influence is minimal in the north aspect.

Acknowledgements

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