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ORIGINAL ARTICLE

Topography-dependent climatic sensitivities in spruce tree growth in the Changbai Mountain, Northeast China

Shoule Wang[1,2,3] · **Xiaoyu Wang**[4] · **Xuerui Gai**[5] · **Li Zhou**[2] · **Wangming Zhou**[2] · **Yangang Han**[2,3] · **Dapao Yu**[2]

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Abstract

Key message **We explored topography-dependent variations of spruce (Picea jezoensis var. komarovii) growth in response to climatic change, and abrupt decline in its climatic sensitivities to temperature under global warming in the Changbai Mountain, Northeast China.**

Variations in the mountain slope direction, being different in radiation intensity and soil moisture, might exert a profound influence on the growth-climate relationship, which potentially brings indeterminacy in sensitivity to temperature under climate warming. To better understand the spatial variation in this influence, we used dendrochronological methods to determine the relationship between the radial growth of spruce (***P. jezoensis*** var. ***komarovii***) and climate in three aspects at an elevation of approximate 1200 m in the Changbai Mountain. The results indicated obvious correlations among the three spruce chronologies, and the radial growth presented more positive correlations with spring temperature (rather than summer or winter temperature), with April temperature on the south-facing slope and negative with precipitation on the north- and west-facing slopes. Despite the sensitivities to temperature were abruptly declined by the increasing temperature, the year- occurrences were inconsistent with records from 1996, 1995 and 1989 on the north (in May), west (in May) and south (in Apr), respectively. The negative relationship with May precipitation has become stronger since 1982 on the north and west for the increasing amount of precipitation. Therefore, given the declined sensitivity of spruce growth to climate warming, which can be shown among three different slopes, the divergent point would be difficult to precisely disentangle in investigating the temporal stability base on the variation in species, habitat and data analytical method.

Keywords Radial growth·sensitivity · *Picea jezoensis* · Slope directions · Changbai mountain

Introduction

The slope aspect of a mountain determines the sunshine hours and solar radiation intensity and thus it plays an important role in the mountain ecology. In general, the northern slope has a lower air temperature, smaller light intensity, higher relative humidity and richer soil nutrients than the southern slope in the northern hemisphere (Zhang et al. 2015; Bardelli et al. 2018; Cao et al. 2020; Yang et al. 2020). These slope-related differences in ecological environments significantly change plant composition, community structure and the relationship between plants and ecological environments. Recent evidences about the spatial pattern of tree growth and mortality to drought stress on mountain slopes further highlighted that slope might mediate tree growth patterns in response to climate change (Kharuk et al. 2016; Leonelli and Pelfini 2016; Klippel et al. 2017).

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✉ Dapao Yu
yudp2003@iae.ac.cn

[1] Xinjiang Institute of Ecology and Geography Chinese Academy of Sciences, Urumqi 830011, China

[2] Chinese Academy of Sciences, Key Laboratory of Forest Ecology and Management, Institute of Applied Ecology, Shenyang 110016, China

[3] University of Chinese Academy of Sciences, Beijing 100049, China

[4] Jiyang College of Zhejiang A and F University, Hangzhou 311300, China

[5] Shenyang Normal University, Shenyang 110034, China

Many studies have demonstrated that there are significant differences in tree radial growth and the responses of tree growth to climate for a given tree species among slope directions (Bunn et al. 2005; Xiao et al. 2015; Papadopoulos, 2016; Klippel et al. 2017). For example, Fekedulegn et al. (2003) found that yellow poplar has a defined aspect preference, showing a higher mean ring-width at sites on the south-facing slope than that at sites on the north-facing slope in an Appalachian watershed. Liang et al. (2010) found a dramatic difference in the response of the growth of *Sabina przewalskii* and *Picea crassifolia* to climate variables between the east- and west-facing slopes on the Tibetan Plateau. Generally, tree growth on the south-facing slope might be susceptible to water, while it could be susceptible to temperature on the north-facing slope (White et al. 2011; Bi et al. 2015; Zhang et al. 2015; Kimball et al. 2017; Sohar et al. 2017). Different climatic responses have changed the competitive strength among tree species, which is one of the reasons for different forest structures on various slopes. Therefore, exploring the difference in tree growth of a given tree species to climatic response among slopes is constructive for understanding or predicting slope-specific plant dynamics under climate change scenarios.

In recent years, a large number of studies have reported that the growth-climate relationship has changed with time due to the effect of global warming (D'Arrigo et al. 2008; Liang et al. 2010; Dang et al. 2012; Sanchez-Salguero et al. 2018; Du et al. 2020). This discovery raised a challenge to the established basic hypothesis of the dendrochronology "uniformity principle" related to the radial growth-climate relationship and thus added a great deal of uncertainty in predicting tree growth dynamics under climate change scenarios. According to published documents, the major inducement of instability in the relationship is climate warming-drying. The warming and drying climates result in soil water deficits (exceeding the water threshold) or temperature-induced physiological changes in trees (exceeding the temperature threshold of normal growth or dormancy). Therefore, trees growing at the lower limit of their distribution, similar to that at the upper distribution, are likely to experience instability in the growth-climate relationship in humid temperate regions (Shen et al. 2016; Sohar et al. 2017; Wang et al. 2017). Additionally, given the variations in moisture and heat that occur with slope aspect under climate warming-drying conditions, the stability of tree growth-climate relationships might express obvious differences. In fact, many studies have confirmed instability in the relationship between ring width and summer temperature over time among different slopes (Fekedulegn et al. 2003; Liang et al. 2006; Leonelli et al. 2009). These findings all pointed out that testing the slope-specific stability of the growth-climate relationship is important for predicting mountain forest dynamics.

The Changbai Mountain is located on the border between China and North Korea, whose northern, southern and western slopes are within China's territory. It is the highest mountain in Northeast China, with a clear gradient in the vertical distribution of vegetation, and has long been considered an ideal area for dendrochronological studies (Shao and Wu 1997; Fang et al. 2016; Wang et al. 2016; Yu et al. 2016). Spruce (*P. jezoensis* var. *komarovii*), one dominant species in spruce-fir mixed forest ranging from ~ 1100–1700 m asl, is known to be sensitive to climate variations in the Changbai Mountain (Yu et al. 2006, 2013). The spruce trees that grow at or close to their lower distribution boundary, similar to that at the upper distribution, suffer more from climate warming, and its growth-climate relationship might be more vulnerable to climate warming in the Changbai Mountain (Yu et al. 2006; Li et al. 2011; Wang et al. 2017). However, tree composition is different at low elevations (1200 m) on the three slopes. Specifically, it is dominated by spruce (40%), fir (20%) and broadleaved tree species (20%) on the northern slope, by spruce (45%), fir (20%) and larch (30%) on the southern slope, and by spruce (30%), fir (10%), pine (10%) and broadleaved tree species (40%) on the western slope. The difference among the three reflects the climate conditions affecting the habitat in which the tree species grow (Xiao et al. 2015). To date, most studies on spruce have focused on the north-facing slope, with temperature as the major limiting factor at higher latitudes and precipitation as the more limiting factor at lower latitudes (Wang et al. 2016; Zhuang et al. 2017). Furthermore, several studies on the north-facing slope have confirmed that the spruce radial growth relationship has changed with time (Li et al. 2011; Yu et al. 2013; Fang et al. 2016; Shen et al. 2016). However, few studies have been conducted on west- or south-facing slope, which makes it difficult to understand the topography-dependent response in tree growth to climate.

Given that the slope direction mediates the climate conditions, we hypothesized that the spruce growth-climate relationship and its stabilities vary with the slope under global warming scenarios. In this study, we used dendroecological methods to analyse a tree-ring network based on the data of spruce on the north-, west- and south-facing slopes at an elevation of 1200 m in the Changbai Mountain. The objectives were to (1) explore the sensitivity of radial growth to climate; (2) determine the climate variables limiting spruce radial growth; and (3) detect the stability of the growth-climate relationship among different slopes.

Materials and methods

Study area

The study was conducted in the Changbai Mountain Natural Reserve (CMNR) (41°31′-42°28′N, 127°9′-128°55′E) in

Northeast China (Fig. 1). The area has been less distributed by anthropogenic activity because the CMNR was not exploited for tourism until the 1980s and became a protected nature reserve in 1960. The altitudinal vegetation zonation in the mountain is well documented (e.g.Wang et al. 1980; Yu et al. 2004). There are four vegetation zones recognized along the altitudinal gradient.

The spruce-fir (*Abies nephrolepis* Maxim) forest zonation extends from approximate 1100–1700 m asl, with a slight difference among slopes, specifically from 1100 to 1700 m asl on the north-facing slope and from 1100 to 1600 m asl on the west- and south-facing slopes. Spruce individuals are distributed from approximate 900–1800 m asl on all three slopes within the territory of China.

The study area is characterized by cold, windy winters and warm, wet summers. The climatic records from three meteorological stations were compiled under the China Meteorological Data Service Center (CMDC) (Table 1). Three meteorological stations—Erdao, Donggang and Changbai—are the nearest stations to the sampling sites on the north-facing, west-facing and south-facing slopes of CMNR, and these sites can support a long time series to represent regional climatic conditions (Fig. 1).We calculated temperature at other elevations using a lapse rate of 0.6 °C (Li et al. 2011), and precipitation using an increment rate of 22 mm/100 m from the elevation 600 m to 1200 m (Yang 1981). In the study area, at an elevation of ~ 1200 m the annual mean temperatures are – 0.01, 1.14, – 0.03 °C and

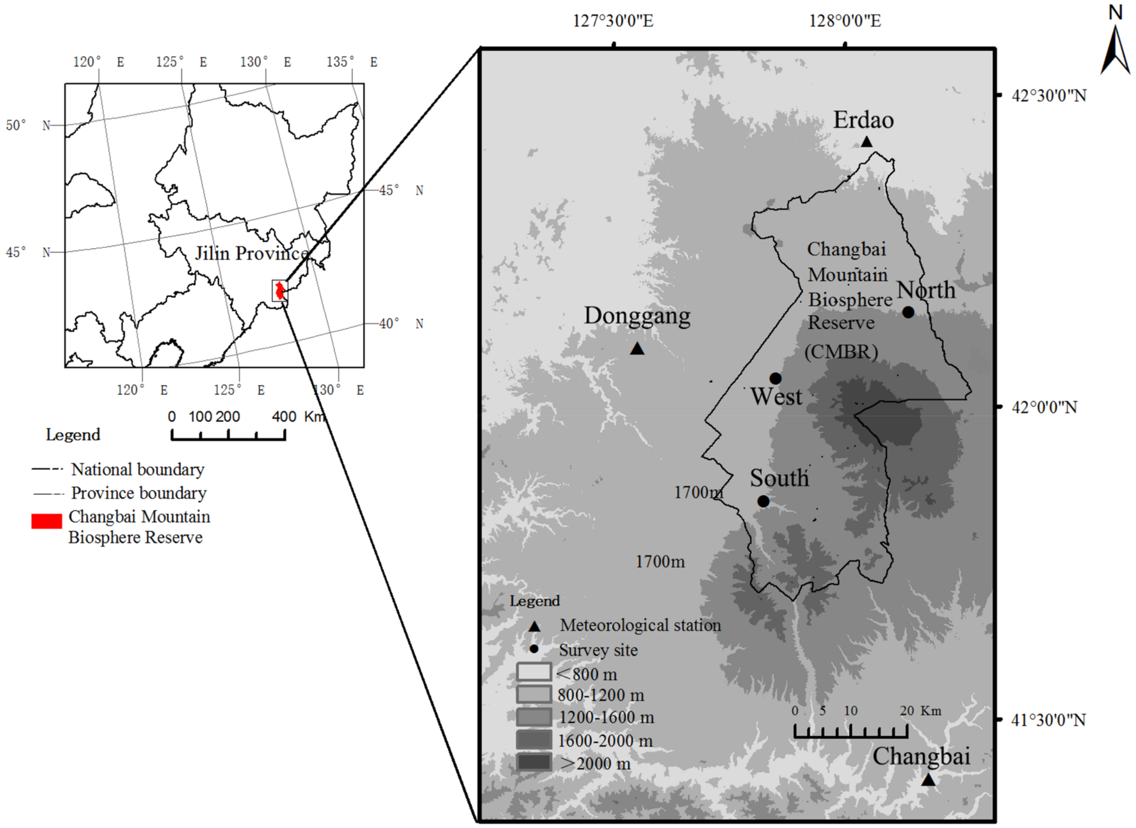

Fig. 1 Locations of Changbai Mountain Natural Reserve and meteorological stations

Table 1 Information about sampling sites and meteorological stations (adjacent)

Meteorological Stations	Slope	Latitude N	Longitude E	Elevation (m)	Recording period	Annual average temperature (°C)	Annual precipitation (mm)
Erdao	North	42˚05’	128˚07’	721	1958	2.86	677
Donggang	West	42˚06’	127˚34’	774	1957	3.70	823
Changbai	South	41˚25’	128˚11’	775	1957	2.50	664

the total precipitations are 782, 917, 758 mm on the north-facing, west-facing and south-facing slopes, respectively. The correlation coefficients in the annual mean temperature exceed 0.75 among all three slopes. Approximate 80% of the total annual precipitation occurs between Jun and Sep (Fig. 2).

Field sampling

The sampling sites were selected along with the aspects at an elevation of approximate 1200 m on the three slopes (north, south and west) of the CMNR in the year 2015 and 2016. We have only sampled trees at the elevation of ~ 1200 m because trees at the lower distribution are analogous to the upper distribution. The spruce growth was closely related to temperature and precipitation, and the spruce-fir forest might suffer greatly from the influence of climate warming. Additionally, the upper distribution at an elevation of ~ 1700 m is mainly dominated by larch, not spruce-fir forest in the west-facing slope. The current sampling area is the westernmost part of the spruce distribution on CMNR because the windstorm in 1986 has blown down most of the large spruce individuals.

At each slope site, at least 20 healthy and large spruce individuals in the forest canopy were sampled, and two or more cores were collected from each individual at breast height (~ 1.3 m) as close as possible to the pitch.

Development of chronology

All cores were dried, mounted, sanded, and visually cross-dated. The tree-ring widths were measured to an accuracy of 0.001 mm using the Lintab system. All ring series were checked for missing and pseudo rings using the programme COFECHA. All tree cores that had presented with difficulties in the ring identification and/or cross-dating processes were eliminated from the site chronology.

To obtain growth chronologies with low-frequency information, the ARSTAN programme was used to detrend the series with a negative exponential curve and a straight line with a negative slope to remove the non-climatic growth trend, which might result from age and size differences embedded in ring-width series.

These individual dimensionless index series were averaged together using a bi-weight robust mean to develop three standardized chronologies (STD). Then, the remaining temporal autocorrelation was removed by an autoregressive model to obtain the residual chronologies (RES) (Cook 1985), which would contain higher characteristic values and be better for assessing climate-growth relationships (Fig. 3).

The growth-climate relationships

Using SPSS 19.0, the relationship between climate and tree radial growth was investigated by correlating the ring-width index with climatic variables, including mean monthly temperature (T_m), maximum monthly temperature (T_{max}), minimum monthly temperature (T_{min}) and monthly precipitation (Pre). Given that the RES chronology has removed from the lagged effects of climatic variables on spruce growth, climate data were extended over a 12 months window from Nov of the previous year to Oct of the current year. To explore the effects of seasonal climatic variables on spruce, the months were grouped into several seasons using the mean monthly temperature values. Seasonal classification included winter (pre-Nov–Mar, $T_{max} < 0$), spring (Apr–May, $T_{min} > 0$, $T_{max} > 5$), summer (Jun–Aug), and autumn (Sep–Oct, $T_{min} > 0$, $T_{max} > 5$). We also detected the variability of the relationship between climate and spruce

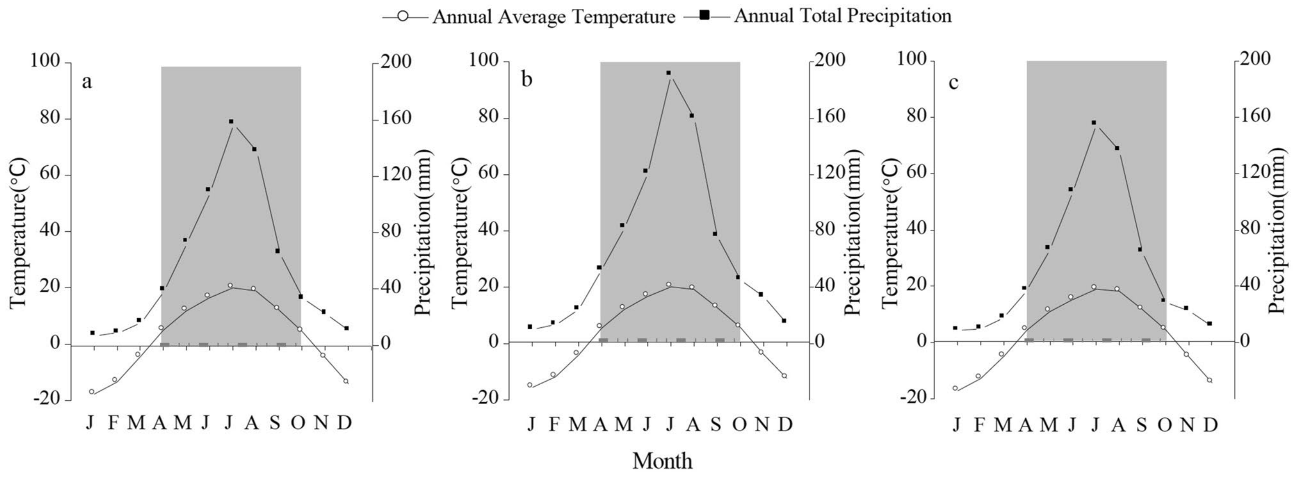

Fig. 2 Monthly total precipitation, mean temperature, and maximum and minimum temperatures in the study area from 1958 to 2014, based on records from the Erdao **a**, Donggang **b** and Changbai **c** meteorological stations. The shadow represents the main growing season of plants from Apr to Oct

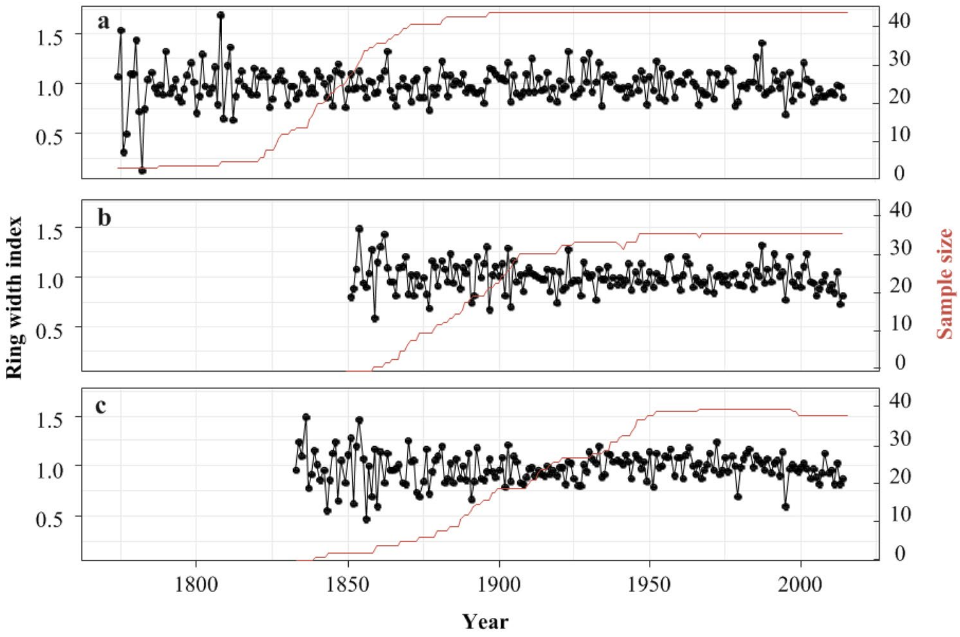

Fig. 3 The residual chronologies of *P. jezoensis* in sampling sites of the north- **a**, west- **b**, south- **c** facing slopes, and the corresponding sample size (number of tree cores)

growth using moving correlation. In this study, the relationship of climate and its moving correlation was conducted to explore the effect of climate variables on climate-growth stability.

Results

Chronology characteristics

The three slopes were different in terms of the age structure and the ring width of the trees that were sampled in Changbai Mountain. Comparing to trees from the sites on the north-facing slope which could be dated back to the 1770s, the trees on the west- and south-facing slopes could only be dated back to the 1830 and 1850s, respectively (Fig. 3). The average width of cores in the common period ($SSS > 0.85$) was 1.63 mm in the south and 1.53 mm in the west, which were 63 and 53% higher, respectively, than that in the north (1.00 mm) (Table 2).

The mean sensitivity (MS), standard deviation (SD) and first-order (lag-1) autocorrelation coefficient (AC1) statistics, used to assess the statistical-dendroclimatological quality of the three slope chronologies, are given in Table 2. Among the three slopes, the chronology on the north-facing slope had the largest MS and SD. Moreover, the mean correlations among cores (rbr), the signal to noise ratio (SNR), the express population signal (EPS) and the first principal component of the variance (PC1) had all the highest values in chronology on the north-facing slope. Meanwhile, all of the characteristics for the south- and west-facing slope chronologies were similar (Table 2). Although differences in the statistical characteristics were found, the three slope chronologies had a significantly positive and similar correlation (Table 3).

Growth–climate relationship

On the north-facing slope, the radial growth of spruce trees significantly and positively correlated with T_m and T_{max} in May and Jan precipitation, but negatively with T_{min} in Mar

Table 2 Statistical characteristics of *P. jezoensis* chronologies

Sites	Cores (trees)	Ring-width (sd)/mm	Time span ($SSS = 0.85$)	MS	SD	AC1	rbr	SNR	EPS	PC1
North	42 (23)	1.00 (0.46)	1828–2014	0.179	0.166	− 0.070	0.305	16.69	0.943	32.96%
West	37 (19)	1.53 (0.77)	1880–2014	0.136	0.124	0.022	0.250	8.99	0.900	29.19%
South	41 (22)	1.63 (1.04)	1879–2014	0.137	0.124	0.040	0.271	9.67	0.906	30.52%

SSS 0.85 refers to information for subsample signal strength attaining 0.85, *SD* standard deviation, *MS* mean sensitivity, *AC1* first-order autocorrelation, *rbr* mean correlations among all cores, *SNR* signal to noise ratio, *EPS* express population signal, *PC1* variance in the first principal component

Table 3 Correlations among *P. jezoensis* chronologies on three slopes (1880–2014)

Aspect	North	West	South
North	1		
West	0.520**	1	
South	0.467**	490**	1

Asterisk, doube asterisk stand for a significant correlation at 0.05 and 0.01 level (2-tailed test)

and Jan and May precipitation (Fig. 4). On the west-facing slope, radial growth positively correlated with precipitation in May and Jun and Apr T_{max}. On the south-facing slope, however, a positive correlation occurred with Apr T_m, while a negative correlation was found with Jun T_{min} (Fig. 4).

In the seasonal windows, it was found that the results from the correlation analysis between climate variables and the chronologies were consistent with those from monthly variable analysis, in which T_{max} in the current spring has serious impacts on spruce growth on the north- and west-facing slopes (Fig. 4). Some strong correlations with spring precipitation occurred on the north- and west-facing slope ($P < 0.05$), while not on the south-facing slope.

The stability of the growth-climate relationship

A 25 year moving window was exhibited to detect the temporal variability in the radial growth response to climate factors during the period of 1958–2014 (Fig. 5). On the north-facing slope, a significant and positive correlation with T_{max} in May remained higher on a long timescale, and it even showed an upward tendency (Fig. 5b). However, the positive

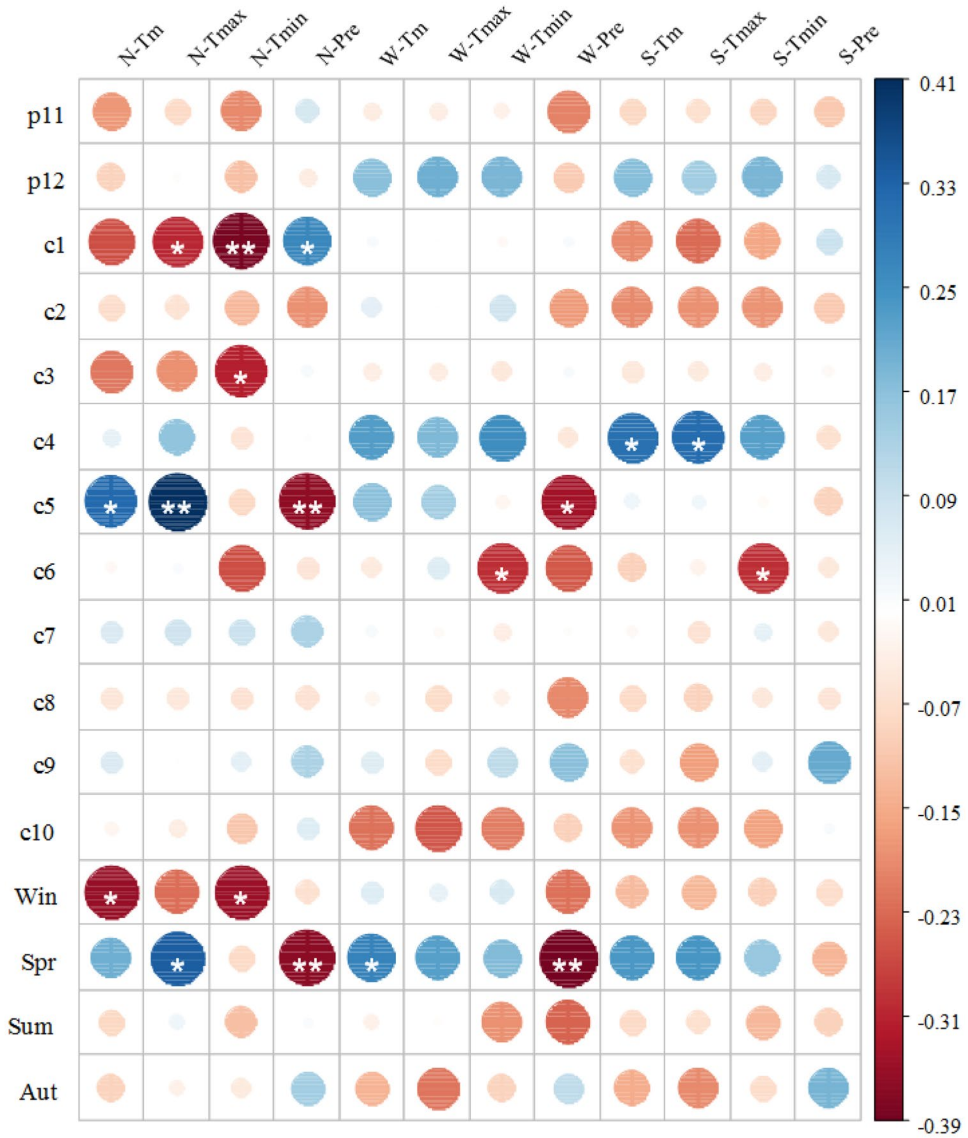

Fig. 4 Strength of Pearson correlation coefficients between chronologies of spruce and monthly (pre-December to cur-August)/seasonally (winter to autumn) climatic variables on the north (N), west (W) and south (S). Win, Spr, Sum, and Aut represent winter, spring, summer and autumn, respectively. asterisk, doube asterisk stand for a significant correlation at 0.05 and 0.01 level (2-tailed test)

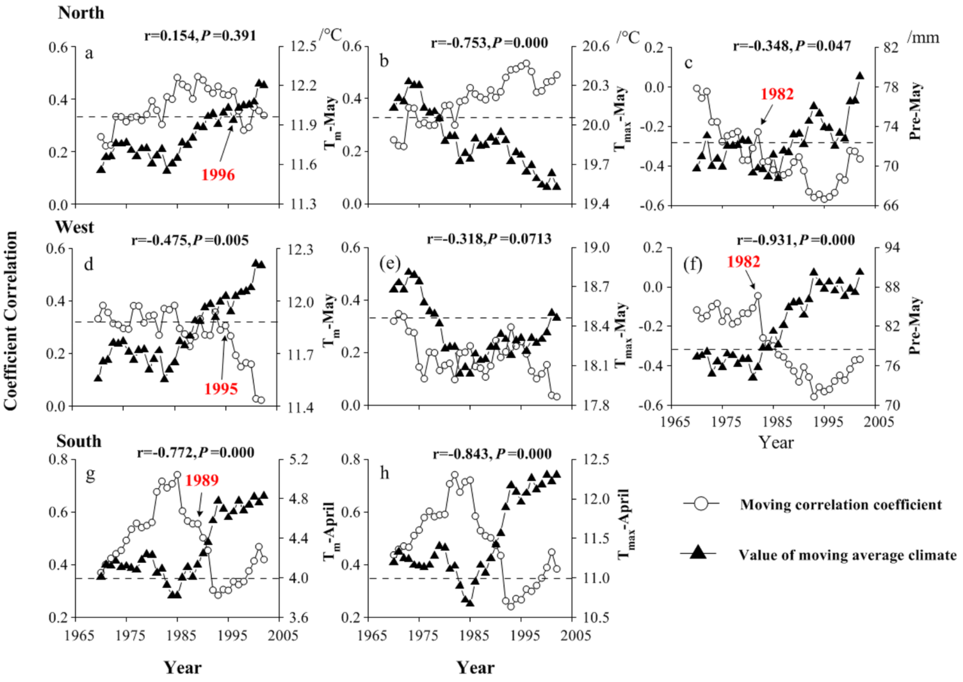

Fig. 5 Results from the 25 year moving window correlation between tree-ring width and climate data and the 25 year moving average values for monthly temperature and precipitation. T_m, T_{max}, Pre in May and correlations with spruce chronologies on the north-(**a**, **b**, **c**) and west-facing (**d**, **e**, **f**) slopes, respectively. T_m, T_{max} in Apr and correlations with spruce chronology on the south-facing (**g**, **h**) slope. Horizontal dashed lines indicate the $p < 0.05$ significance level

correlation with T_{max} decreased since 1996, and the negative correlation with May precipitation strengthened (Fig. 5a, c). On the west-facing slope, the positive significance of the relationship between spruce growth and temperature in May was no longer visible in recent decades since 1995 (Fig. 5d), while the negative correlation with precipitation has increased over time since 1982 (Fig. 5f). On the south-facing slope, the sensitivity to T_m and T_{max} in the current Apr was significantly positive (Fig. 5g, h) but obviously declined after approximate 1989.

T_m in May and Apr, which could produce a significant influence on spruce growth, increased since 1996, 1995 and 1989 (Fig. 5a, d, g), and the precipitation in May increased since 1982 (Fig. 5c, f). Except for the western slope, T_{max} decreased in May and increased in April (Fig. 5b, h). These were considered to be positive factors regarding the attenuating sensitivity to climate. The correlation between the moving correlations and climatic variables indicated that climate change has a strong influence on the stability of the climate-growth relationship. The effect of T_{max} in May and Apr on the moving correlation was significantly negative on the northern and southern slopes. In addition, the growth-precipitation correlation was significantly negative with May precipitation on the northern and western slopes.

Discussion

The radial growth and chronology quality

The spruce sampling among the three sites showed significant differences in growth, where the south- and west-facing slopes experienced higher mean diameters than the north-facing slopes did. This phenomenon could be explained by the variation in environmental conditions as aspect shifts, in which spruce on the south-facing slope receive more solar radiation favourable for growth. The mean sensitivity (MS) exceeded 0.12, and the expressed population signal (EPS) ranged from 0.900 to 0.943, which is considered a benchmark of the signal strength of a chronology (Cook et al. 1990). It was found that chronological statistics indicated that there were effective differences between aspects (Table 2). The MS and SD values were higher on the north-facing slope than those on the south-facing slope, which revealed that the regional spatial difference in spruce growth was also largely influenced by the topographic features, even in the same region (Papadopoulos 2016). This result suggested that the northern slope was more suitable for dendroclimatological analysis. Despite the evident variations in the chronological statistics and average ring width in the common period of 1892–2014, the higher correlations (above 0.46) among the three chronological indices indicated that spruce growth had a consistent response to regional conditions.

The relationship between growth and climate

The three slope chronologies presented significant correlations with T_{max} in spring, while they had a weak correlation with the summer and winter climatic variables; this result indicated that the temperature in the current Apr or May played a critical role in spruce growth in the Changbai Mountain (Yu et al. 2006; Wang et al. 2017). Previous studies have suggested that winter temperature and summer temperature are key factors affecting tree growth in temperate regions (Nishimura and Laroque 2011). However, spring temperature is an important variable for the spruce-fir forest. At the beginning of the growing season, warmer temperatures stimulate early cambium activities effectively to widen tree rings. In addition, the significant influence of May temperature on spruce growth, even at high altitudes in the Changbai Mountain, has been established in similar studies (Yu et al. 2006; Li et al. 2011; Wang et al. 2017).

Furthermore, the relationship between the growth and climate varied with the topographic aspects in this study. On the north-facing slope, the higher T_{min} in January showed a negative influence on tree radial growth because the lower temperature caused stronger respiration, which leads to a greater consumption of nutrients (Gea-Izquierdo et al. 2012). Similar findings regarding the negative impacts of winter temperature on larch forests were reported in Hauck et al. (2016) and Su et al. (2015). The radial growth was significantly and negatively correlated with precipitation in May on the north- and west-facing slopes. The increased precipitation in May made the soil accumulate a considerable amount of water so that roots could not accomplish aerobic respiration, which in the end hindered the absorption of soil nutrients (Gao et al. 2011). Reduced solar radiation always influences plant photosynthesis as precipitation continues (D'Arrigo et al. 2008). On the south-facing slope, no significant correlation with May climatic variables was found, but the temperature in Apr was a significant limit. Habitat types have regional differences in environmental conditions, and these differences affect the growth-climate relationship deeply. Spruce on the south-facing slope showed a reduced response to spring precipitation because receiving more solar radiation and accelerating vegetation growth earlier weakened the negative effect of precipitation on spruce (Zhang et al. 2015; Klippel et al.2017). The results indicated that spruce growth is closely related to temperature and precipitation on the north-facing slope and to temperature on the south-facing slope, which is consistent with the results from previous studies (e.g., Makinen et al. 2002; Leonelli et al. 2009; Zhang et al. 2015).

Spatial response to recent climate warming

Temporal variations in the growth-climate relationship were clearly exhibited (Fig. 5) and mainly affected by topographic aspects under the progressively warming climate. These results suggested that the increasing temperature might build up a higher requirement for water and that would make drought stress a growth driver for spruce as shown in recent decades (Driscoll, 2005; Yu et al. 2006; Zang et al. 2011; Walker and Johnstone 2014; Primicia et al. 2015). The unstable relationship between growth and temperature is similar to that at high elevations in previous studies (Berner et al. 2011; Lebourgeois et al. 2011; Salzer et al. 2014; Galván et al. 2015). In addition, the increasing precipitation and stronger correlation indicated that an increased amount of rainfall in the growing season is not beneficial for spruce growth for bringing the sensitivity to precipitation. Though the declined sensibility to temperature was apparent in this study, year-occurrences were inconsistent among the three slopes. In previous studies, Shen et al. (2016) explored the climate variables and regarded 1988 as a critical point to determine the larch growth sensitivity to climate. Cao et al. (2018) adopted the sharply increased temperature to figure out the change-point (1984) for the rapid warming and discuss the "Divergence Problem". Hence, the variation in year-occurrence might have to do with the analysis method used, species, sample sizes, and even detrending methods (D'Arrigo et al. 2004; Buntgen et al. 2012; Shen et al. 2016; Han et al. 2019). Besides, the difference in slope directions influences forest distributions and conditions of sampling point, and may conflict with the stability of the growth-climate relationship. It should be mentioned that the spruce growth was affected by the temperature in May in the north while in April in the south, which implied that slope causes a shift in the growth-climate relationship and might impact the sensitivity to climate warming. Meanwhile, the sampling mode related to the stand structure and spruce distribution might express and extrapolate the stability of the growth response to climate in habitat (Zhang et al. 2013; Camarero et al. 2018). Multi-point layout should be adapted to combine individual analysis and integral analysis to comprehensively discuss the climate sensitivity (Han et al. 2019). In conclusion, this study indicated that global warming would make an important impact on the sensitivities to climate change of spruce in the Changbai Mountain in the future.

Conclusions

Topographic aspects have great influences on species composition as well as the tree growth-climate relationship in the Changbai Mountain, Northeast China. The results suggested that the temperature in spring—but not that in summer or winter—plays a critical role in spruce growth. Spruce radial growth was affected by spring precipitation on the west- and north-facing slopes. A decreasing and positive correlation with temperature was found among three slopes which may be caused by the increasing temperature, but the change-point of declining on each slope was apparently different (north, 1996; west, 1995; south, 1989). The correlation with May precipitation was aggravated by increasing precipitation on the north- and west-facing slopes. Therefore, this study could be greatly helpful to research the topography-dependent climatic sensitivities of tree growth and forest distribution under global warming.

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Author contribution statement Dr. SW, Dr. XW and Dr. XG prepared the sample for measurements and analysis. Dr. LZ and Dr. WZ provided overall guidance for this study. Dr. YH helped on analysing data. Dr. SW analysed data and wrote the manuscript. Dr. DY designed the experiment and co-wrote the manuscript.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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