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The impacts of climate change on the radial growth of *Pinus koraiensis* along elevations of Changbai Mountain in northeastern China

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ABSTRACT

The importance of a better understanding of the growth response of forest to climate change for managing and conserving forest has been realized. In this study, we developed the ring-width chronologies of Korean pine (*Pinus koraiensis*), one of the main constructive species of Changbai Mountain in northeastern China, to examine the radial growth–climate relationships. The stability of these relationships before and after abrupt climate change was evaluated. We built regression equations to project the future growth of the species under future climate change scenarios projected by the Providing Regional Climates for Impacts Studies (PRECISs) climate model. The results were as follows: (1) The chronologies in the three elevation gradients, HY1 at 740 m.s.l., FA at 940 m.s.l. and HY2 at 1258 m.s.l., had the good spatial similarity with high Gleichläfigkeit (GLK) indices; however, significant differences still existed between the growth–climate relationships of the three sites. The width chronology of Korean pine at site HY1 was positively correlated with the precipitation in September of the previous year ($p < 0.01$) and June of the current year ($p < 0.05$). The chronology at site FA was positively correlated with the temperature in March and April of the current year ($p < 0.05$). Whereas the current July temperature and the previous September precipitation were the main limiting factors for the growth of Korean pine at site HY2. (2) Mann–Kendall test results revealed that the climatic data from the meteorological stations near the sampling sites had an abrupt annual average temperature change in 1989, but the radial growth–climate relationship change only occurred in the chronology with May precipitation at site HY2, which may be caused by water stress. (3) With the projected increasing temperature and decreasing precipitation, compared with the base-line period (1971–2000), the radial growth of Korean pine at HY1 will relatively decrease, and the reduction will gradually increase. In contrast, at the higher elevation, like the FA and HY2 sites, the radial growth of Korean pine will relatively increase. Thus, the higher elevation areas of the Korean pine's vertical distribution belt are more favorable for this species' radial growth and forestation.

1. Introduction

The elements of climate affect the forest microclimates, the operational environments and the physiological processes, which in turn control growth (Fritts, 1976). The recorded climatic data shows the global warming phenomena (IPCC, 2007), and this global climate change has led to forest growth change through extending the growing season and increasing photosynthesis especially in the northern latitudes (Lindner et al., 2010). The future climate change will also influence the forest growth; for example, the forest growth reductions were found in southern United States under projected climate change in 21st century (Chen et al., 2010). Additionally, climate change can affect forest in other aspects, such as forest distribution and species composition (Crimmins et al., 2011). Therefore, a better understanding of forest growth response to past climate variability and the projected climate change has been in an increasing requirement to maintain productive and sustainable forest (Lindner et al., 2010; Parks and Bernier, 2010).

Tree-ring as an indicator of the radial growth of trees is highly sensitive to climate change. The dendroclimatology method uses the tree-ring variables such as ring widths to examine radial growth–climate relationship by correlation analysis. This method has been proven to be an effective method to observe forest growth responses to climate change (Krakauer and Randerson, 2003; Chen et al., 2010; Lapointe-Garant et al., 2010; Zhang et al., 2012). However, the growth–climate relationships built by dendroclimatology method have been found instable in some studies (Briffa et al., 1998; Lloyd and Bunn, 2007; Büntgen et al., 2008). Therefore, the

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correlations between climate elements and tree-ring chronologies observed during a time period should be checked with the stabilities during this period before being applied in the projections of tree growth in future.

Changbai Mountain, at the core area of the vegetation zone in northeastern China, covered with a large area of undisturbed temperate old-growth forest (Shao and Zhao, 1998). The forest is sensitive to climate change and has experienced climate warming over the past 50 years (Zuo et al., 2004; Guo et al., 2005; Ren et al., 2005), which made Changbai Moutain became an important dendroclimtology studies region in China. Korean pine (*Pinus koraiensis*) is the main constructive coniferous species in Changbai Mountain, and distributes geographically from 35°E to 53°E and from 126°N to 140°N which covers southeastern Siberia, the northeastern provinces of China, northern Korea and the Japanese islands of Honshu and Shikoku (Hutchins et al., 1996). Lots of studies on the relationship between the tree rings of Korean pine and climate have been carried out in northeastern China (Shao and Wu, 1997; Yin et al., 2009; Zhu et al., 2009; Gao et al., 2011; Wang et al., 2011; Yu et al., 2011), suggesting the application potential of this species in dendroclimatology studies. However, the conclusions of these studies were inconsistent. The main reasons are that most studies were conducted in relative small sampling area and the sample sites were in different elevations which deeply affect the habitat environment by changing the water and heat distribution, which were neglected by most previous studies. Based on the growth–climate relationship, some studies tried to make projection using dendroclimatology method (Wang et al., 1995; Li et al., 2011; Yu et al., 2011), but these studies did not establish the linkage of growth–climate relationship and climate models; thus, there are few projections about the tree growth change under future climate change simulated by climate models.

To the above uncertainties in the research of Korean pine in northeastern China, establishing a credible radial growth–climate relationship and enhancing the projection abilities using this relationship should be two key questions in researches on tree growth and climate change. The objectives of this study were to discuss the Korean pine growth–climate relationships along the elevations of Changbai Mountain and to simulate the Korean pine radial growth changes under the projected climate change scenarios.

2. Methods and materials

2.1. Study area and tree-ring materials

The study area is located on the northern slope of Changbai Mountain Natural Reserve in northeastern China (Fig. 1). The area is adjacent to the Sea of Japan, and the climate is deeply affected by the East Asian monsoon. At Donggang and Erdao stations (data from the National Meteorological Information Center of China, Fig. 1), the mean annual temperature is 3.2 °C, with a mean temperature of −16.7 °C in January and 20.1 °C in July during the period of 1958–2007 (Fig. 2). The mean total annul precipitation is 745 mm, mainly falling during May–September. The vertical zonation of the major forest types is particularly obvious on this slope; for example, low mountain conifer and broadleaf mixed forest zone is distributed from 500 m a.s.l. to 1100 m a.s.l., and the mountain dark coniferous forest zone occurs from 1100 m a.s.l. to 1800 m a.s.l. (Editorial Committee for Forestry of Jilin, 1988). The tree-ring cores in the study were sampled in three sites, named HY1, FA and HY2 (Fig. 1), in the above two forest zones. The elevations of these sites varied from 740 m a.s.l. to 1258 m a.s.l. (Table 1).

Cores were mounted and sanded to produce clearly visible boundaries and then were cross-dated (Stokes and Smiley, 1968). The total ring width was measured by the LINTAB measuring system at a 0.01 mm resolution, and the quality of the cross-dating and measurements were assessed using the COFECHA program (Holmes, 1983). The tree-ring chronologies were developed using the ARSTAN program (Cook, 1985). A cubic smoothing spline with 67% of the series length was used to remove the long-term growth trends of the raw ring-width chronologies. The resulting ratio series was then computed as a biweight robust mean of the detrended and standardized individual series (Cook et al., 1990). To show the strength of common signals in the chronologies, a within-chronology common interval analysis for each chronology was performed using the detrended index series. Several statistics were analyzed to measure the quality of chronologies, including the standard deviation (SD), the mean sensitivity (MS), the first-order autocorrelation (AC1), the mean correlation of all series (R), the signal to noise ratio (SNR), variance in the first principal comment (PC1) (Fritts, 1976) and the expressed population signal (EPS) (Wigley et al., 1984). MS is a measure of the annual variability of ring width. AC1 suggests the low frequency signals in the chronology. R and PC1 express the degree of common signals. The threshold value of 0.85 in the EPS is used to evaluate the useful time span of the final chronologies, giving the minimum number of cores which can be used to produce a reliable chronology.

To measure the similarity between any two chronologies, the Gleichläfigkeit (GLK) index was calculated for their common time span from 1846 to 2002. The total Gleichläfigkeit is a measure of the similarity between the trends of two curves at a very high frequency and is usually expressed as a percentage. A larger total Gleichläfigkeit value indicates better agreement between two trends; thus, with a high Gleichläfigkeit value, it can be assumed that the factors influencing growth were similar in both cases (Schweingruber, 1989; Schweingruber et al., 1993).

2.2. Climatic data

Erdao (591 m a.s.l.), Donggang (774 m a.s.l.) and Tianchi (2623 m a.s.l.) are the three meteorological stations near the sites in the study area (Fig. 1), but the Tianchi station data were not used because winter observations were terminated in 1989. The monthly temperature and precipitation correlation coefficients at Erdao and Donggang in corresponding months from 1958 to 2007 were 0.95 and 0.79, respectively. Therefore, we averaged the recorded climatic data from the Erdao and Donggang to improve the regional representative values. The Mann–Kendall test (Goossens and Berger, 1987; Fu and Wang, 1992) was applied to detect the abrupt turning point of climate change.

On the basis of the Special Report on Emissions Scenarios (SRES) issued by the IPCC in 2000, the PRECIS system (Jones et al., 2004) was employed to produce the climatic data in China, with a spatial horizontal resolution of approximately 50 km (Xu et al., 2006) by the Chinese Academy of Agricultural Sciences. Among all of the scenarios proposed by the IPCC, we selected the averaged climatic data for the B2 emission scenario (IPCC, 2007), which is very close to China's national future development plans (Lin et al., 2007). Four periods of the baseline term (1971–2000), the near term (2011–2040), the middle term (2041–2070) and the long term (2071–2100) were included.

2.3. Analysis of the tree growth–climate relationships

We used the correlation analysis by calculating the Pearson correlation coefficient to identify the growth–climate relationships (Fritts, 1974). Because the width of an annual ring can be the result of climatic conditions integrated over a long period, the climatic conditions in the prior year may affect the growth in the current year (Fritts, 1976), and the growing season generally extends from April to September (Zhu et al., 2009). Therefore, the monthly mean

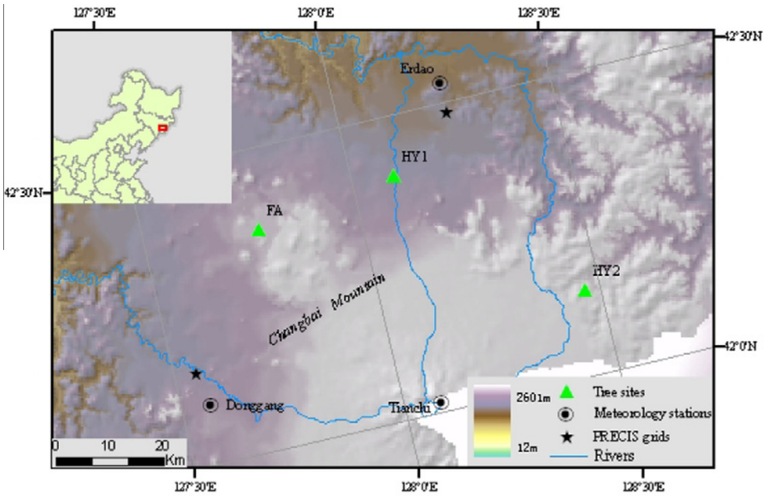

Fig. 1. Locations of the tree-ring sampling sites, the meteorological stations and the PRECIS (Providing Regional Climates for Impacts Studies) grids.

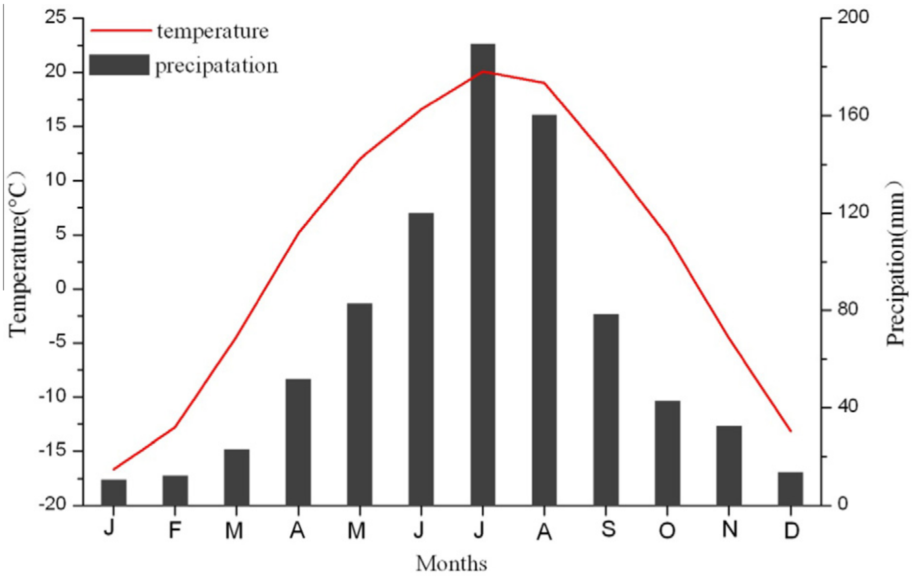

Fig. 2. The long-term monthly mean temperature and precipitation at the Donggang and Erdao meteorological stations, as based on the data for the period of 1958–2007.

Table 1
The sampling site information, the standard chronology statistics and the results of the common period analysis.

	HY1	FA	HY2
Elevation (m a.s.l.)	740	940	1258
Latitude (N)	42.40°	42.37°	42.15°
Longitude (E)	128.1°	127.77°	128.47°
Tree/core	32/65	29/59	29/58
Time period	1846–2007	1689–2002	1797–2007
MS	0.148	0.151	0.115
SD	0.163	0.183	0.146
AC1	0.374	0.487	0.494
Common period	1911–2006	1851–2002	1865–2007
R	0.395	0.349	0.356
SNR	43.977	24.137	22.624
EPS	0.978	0.96	0.958
PC1 (%)	43	36.6	37.6

temperature and total precipitation from the September of the prior year (for the ring formation) to the August of the current year (for the ring growth) were included in the analysis. Due to only meteorological data from 1958 to 2007 could be obtained, the analysis could only be performed since 1959; thus, we analyzed the growth–climate relationships of 1959–2007 for the HY1 and the HY2 sites and 1959–2002 for the FA site.

To investigate the stability of the growth–climate relationship over the entire period, we tested the correlation differences (Lindeman et al., 1980) in the relationships between the tree-ring chronologies and climatic data for the periods before and after the year when the climate changed abruptly.

2.4. Future growth projecting

Based on the relationship results between the tree growth and climate, we built several linear regression equations by a stepwise regression method, using the tree-ring indices as the dependent variables and climatic elements as the independent variables. The variance explained by the equation (R^2) and the significance of the *F*-test (Sig.) were used to select credible equations for the Korean pine growth projections. The climatic data of the baseline term, the near-term, the middle-term and the long-term projected by PRECIS were inputted to calculate the tree-ring width index. We used the relative variation rate (RV) to evaluate the impacts of future climate change on the radial growth of Korean pine, as follows:

$$RV = (Y(X + \Delta X) - Y(X))/Y(X) \times 100\%$$

RV is the relative variation rate; Y is the tree-ring width index; X is the climatic data; ΔX is the variable quantity of temperature and precipitation.

3. Results

3.1. Chronology characteristics at different elevations

Table 1 shows the general characteristics of the individual chronologies. The HY2 site, at the highest elevation, had the lowest mean sensitivity and standard deviation but the highest first-order autocorrelation, whereas HY1, at the lowest elevation, had the highest between-trees correlation, signal to noise ratio and expressed population signal. The EPS of the three chronologies all exceed the recommended threshold of 0.85; according to Wigley et al. (1984), they were all suitable for dendroclimatology studies.

The annual and 5-year moving averaged ring-width indexes revealed the correlations among chronologies in the high-frequency and low-frequency, respectively (Fig. 3). The three chronologies showed the similar variation in the 1880s, circa 1910 and 1960; however, there were also many differences, for example, in the late 1920s, the late 1930s and circa 1980. The Gleichläfigkeit indices (Table 2) illustrated the spatial similarities and differences in the radial growth patterns of Korean pine at the three sites. In terms of the Gleichläfigkeit values, the FA and HY2 had the highest similarity, and the lowest similarity existed between HY1 and HY2, which had the maximum elevation difference.

Table 2
Gleichläfigkeit indices between the three chronologies (1846–2002 year).

	HY1 (%)	FA (%)
HY1		
FA	65.7[a]	
HY2	62.5[a]	68.6[a]

[a] Refers to the significance at 0.01 level.

3.2. Relationships between tree-ring chronologies and climate

3.2.1. Growth–climate relationships along the elevations

The growth–climate relationships were different among the chronologies in three sites (Fig. 4). The width chronology of Korean pine at site HY1 was positively correlated with the precipitation in the previous September ($p < 0.01$) and the current June ($p < 0.05$) (Fig. 4a). The chronology at site FA was positively correlated with the temperature in March and April of the current year ($p < 0.05$) (Fig. 4b). Whereas the current July temperature was the main limit factor for the growth of Korean pine at the HY2 site ($p < 0.01$) and the precipitation in the previous September also affected the growth ($p < 0.05$) (Fig. 4c).

3.2.2. Stability of growth–climate relationships

The annual mean air temperature increased gradually during 1958–2007. From the test results of Mann–Kendall, the intersection of curves c_1 and c_2 between the 0.05 levels of significance localized the abrupt change towards a warming around 1989 (Fig. 5a). The annual average temperature was 2.81 °C before 1989, and then increased to 3.84 °C after 1989. However, the annual total precipitation test result did not single out any of abrupt change, and the annual precipitation had subtle differences before and after 1989 (Fig. 5b).

To investigate the stability of growth–climate relationships, the relationships between the tree-ring chronologies and climate were evaluated for two periods of 1959–1988 and 1989–2007 (1989–2002 for FA), respectively. The test results of the correlation differences (Fig. 6) revealed that there were no significant changes of the correlations at the HY1 and FA sites, and the correlation differences changes at the HY2 site which occurred between the current May precipitation and the ring-width index.

3.3. Growth projections under expected climate change

Significant climate trends were shown by PRECIS predictions (Fig. 7). The annual average temperature increased gradually from the fitting trend line, and the temperature in 2100 was 3.4 °C higher than the temperature in 2011. The annual total precipitation had

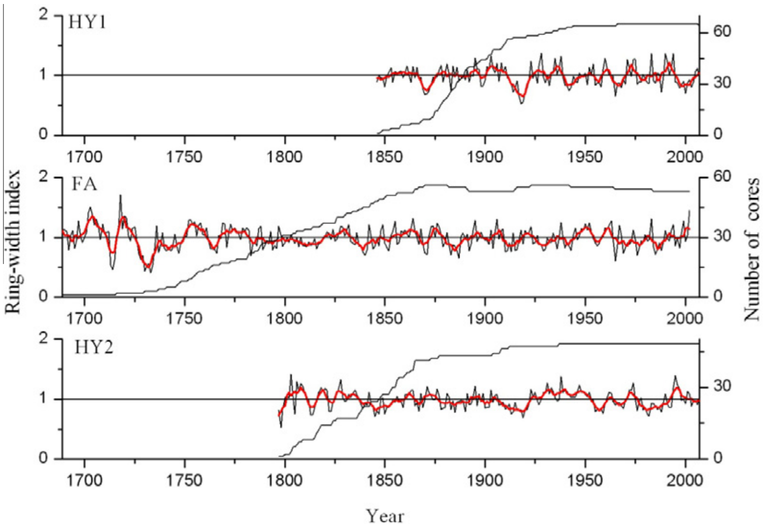

Fig. 3. Ring-width index series of the chronologies and numbers of cores used in the chronology development. The red lines represent the 5-year moving averages. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

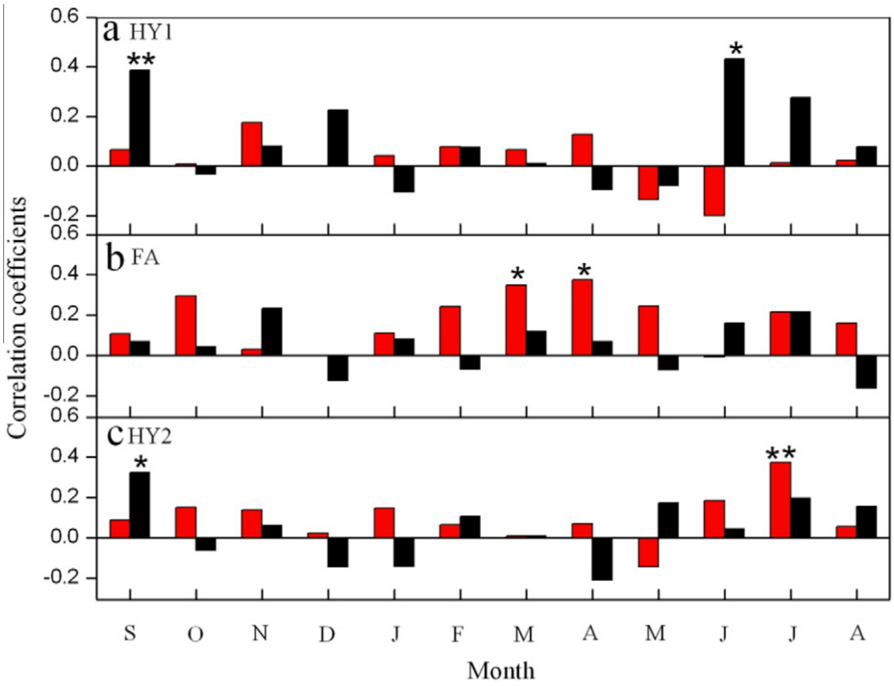

Fig. 4. Correlation coefficients between the monthly climate variables and tree-ring width indices for 1959–2007 (1959–2002 for FA). The red bars denote the temperature, and the black bars denote the precipitation. * Refers to the significance at 0.05 level and ** refers to the significance at 0.01 level. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

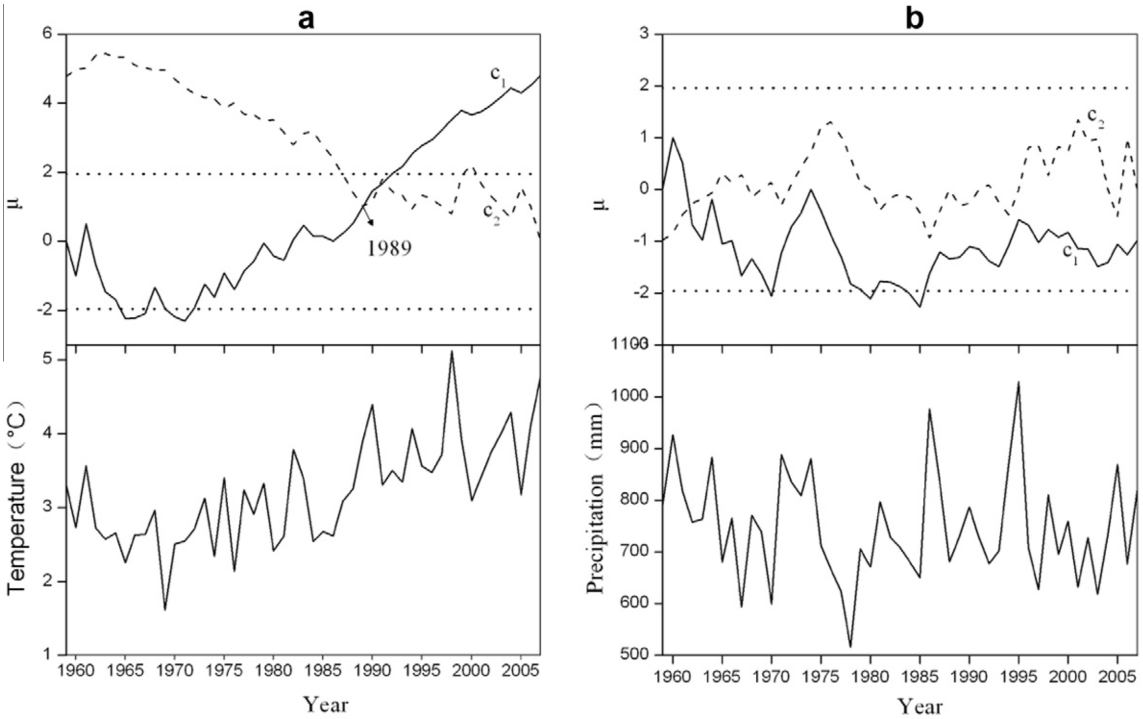

Fig. 5. The variation (upper part) and the abrupt change tested by the Mann–Kendall method (upper part) of (a) annual mean temperature and (b) annual total precipitation. c_1 represent the u values for the normal time series, c_2 represent the u values for the retrograde time series. Dotted lines indicated the value of the 0.05 significance levels.

a decreasing trend, and the precipitation decreased by 158 mm from 2011 to 2100.

The credible regression equations, which passed the significance test at the lowest 0.005 level and have explained variances over 20% (Table 3), were selected for the Korean pine growth projections. As a result, under the expected climate change predicted by PRECIS compared with the baseline term, the growth of Korean pine at the HY1 site will relatively decrease during overall the three future terms, and the relative variation will achieve −4.47% in the long term. Conversely, the growth of Korean pine at the FA and HY2 sites will relatively increase in the future, which will reach 28.60% and 28.63%, in the long term, respectively.

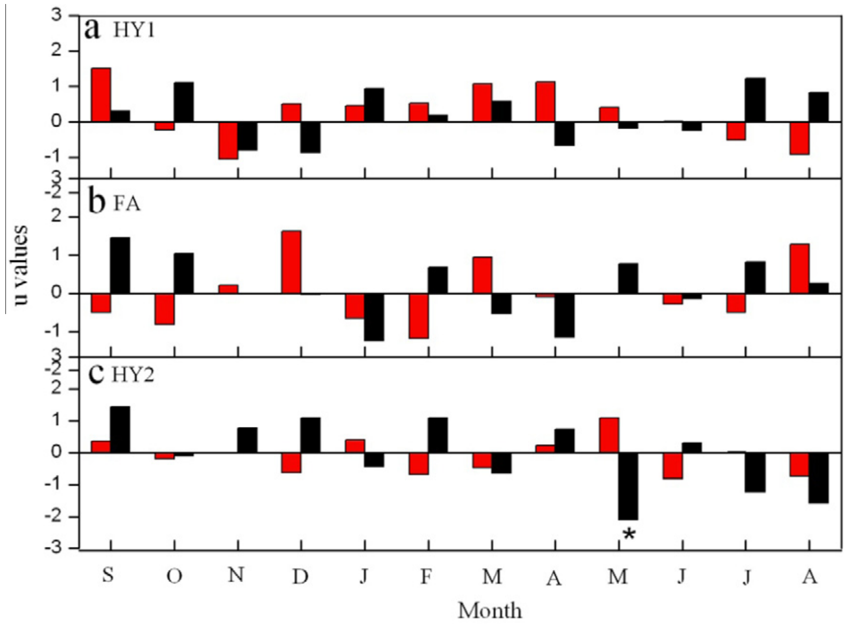

Fig. 6. The results of the correlation differences between the tree-ring indices and climatic data before and after 1989. *U* is the quantile of a standard normal distribution, the value of *u* larger than 1.96 or smaller than −1.96 represents the correlation difference is the significant at 0.05 level. *Refers to the significance at 0.05 level.

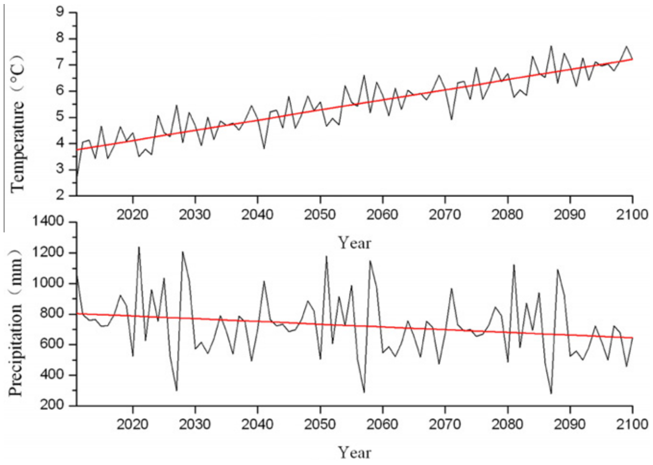

Fig. 7. The monthly climate change during 2011–2100 under the B2 climate scenario. The red lines represent the linear fitting values for temperature and precipitation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

4.1. Climate factors limiting the radial growth of Korean pine along elevations

There were differences in the chronology characteristics and the chronology itself (Table 1), which may be caused by the variation in ecological condition on different elevation; however, the identification of such information requires a comparison of correlation between the chronologies and the climatic data (Wimmer and Grabner, 2000; Fonti and García-González, 2004).

The relationships between the tree-ring chronologies and climate suggested that both temperature and precipitation were the limiting factors for the radial growth of Korean pine on the northern slope of Changbai Mountain and that the specific relationships are closely related to the elevation. This phenomenon was also reported by Yu et al. (2011), the similar elevation-dependent growth–climate relationships were found in the analysis of the growth–climate relationships between *Larix olgensis* (Yu et al., 2005; Chen et al., 2011) and *Picea jezoensis* (Yu et al., 2006), two other dominant conifer species on Changbai Mountain. At the low-elevation site, the precipitation in the previous September and current June mainly limit the growth, a finding which is in agreement with the analysis by Yu et al. (2011). Furthermore, this result proved that precipitation was also a critical factor limiting the radial growth on Changbai Mountain. According to the data recorded at the meteorological stations (Fig. 2), higher precipitation in September results in a greater amount of moisture available in the soil, a situation that is advantageous to the growth of Korean pine in the next year. The precipitation is relatively low at HY1; thus, more precipitation during the growing season can promote tree growth. With an increase of the elevation, the precipitation increases at the middle elevation site; thus, precipitation' limiting effect decreases for Korean pine growth. The FA chronology was positively correlated with the current March and April temperatures, perhaps because high temperature can improve photosynthesis to provide more photosynthate for ring-width growth (Fritts, 1976). As verified by Gao et al. (2011), with further

Table 3
RV values for the three terms (RV = $(Y(X+\Delta X) - Y(X))/Y(X) \times 100\%$).

Regression equation	R^2	Sig.	Near term (2011–2040)	Middle term (2041–2070)	Long term (2071–2100)
HY1 = $0.677 + 0.002P_6 + 0.002P_9$	0.31	0.00	−0.36	−2.46	−4.47
FA = $0.536 + 0.046T_4 + 0.044T_{10}$	0.25	0.00	11.57	20.26	28.60
HY3 = $-0.269 + 0.05T_7 + 0.002P_9 + 0.028T_{10}$	0.29	0.00	11.10	20.03	28.63

T_4, T_7 and T_{10}, are the temperatures for April, July and the previous October, respectively. P_6 and P_9, are the precipitation for June and the previous September.

increases in the elevation at site HY2, the current July temperature was the main limiting factor for the growth of Korean pine because the decreasing temperature may lead to a delay of the onset of the growth period and the termination of growth before the end of the normal growing season.

However, the GLK indices all exceed 60%, illustrating the good similarity among the three chronologies, which was also exhibited in the good agreement of the sign (positive or negative) of the correlation coefficients (Fig. 4). The ring-width chronologies were positively correlated with each monthly temperature, except for May and June. Furthermore, they all had better positive relationships with the precipitation in the previous September and current July and August and had weaker correlations with the precipitation during the other months.

After the abrupt change of the annual average temperature in 1989, which were also found in other studies (Guo et al., 2005; Dong and Wu, 2007; Zhu et al., 2009), the change in the growth–climate relationship only appeared in the HY2 site. The correlation between the HY2 chronology and the May precipitation changed from negative to positive. This result may be attributed to the water stress caused by the increased temperature in the spring, which increased by approximately 1 °C, at the same time the precipitation maintained unchanged. The water stress caused by increased temperature is often considered as the reason for growth–climate relationship changes (Barber et al., 2000; Driscoll et al., 2005); however, this cannot be used to explain the change in the growth–climate relationship at the cell-scale parameters for HY1 (Wang et al., 2011). Accordingly, the reasons and mechanisms should be explored further. In addition, Wang et al. (2011) reported that ring width may be less sensitive than cell-scale parameters, which can record more information for climate change. Thus, the effect of climate change on the growth–climate relationship may require further study based on cell-scale parameters. In general, the correlation between ring width and climate was stable, and we can use the correlation to predict the future growth of Korean pine under the projected climate change.

4.2. Future growth of Korean pine

The projected results revealed that the climate change in the future will cause different changes in the growth of Korean pine at different elevations, which contributes to the different elevation-dependent growth–climate relationships under future climate change. At the low elevation site HY1, tree growths are limited by the precipitation. The projected average precipitation in June and September are lower than 104 mm, the threshold value for Korean pine growth increase relatively according our study, thus, that results in a relative growth decrease at the HY1 site. At the other two sites, the growth of the trees is mainly limited by the temperature, and the future temperatures are expected to increase gradually compared with the baseline term; thus, the tree growth at these two sites will increase greatly.

By using dendroclimatology method, Wang et al. (1995) and Li et al. (2011) found that the ring widths of Korean pine all exhibited an increasing trend as the temperature rose in past decades at either low (Wang et al., 1995) or high elevations (Li et al., 2011), which are inconsistent with our study results. These studies did not build specific equations, but only as a qualitative or semi-quantitative analysis. Yu et al. (2011) projected the future growth of Korean pine at different elevations based on the linear model of the principal component of the ring-width chronologies derived from the temperature and precipitation. This study found that the radial growth at different elevations would increase when the temperature and precipitation change with regard to the self-set values and that the amount of increase becomes larger as the elevation and/or precipitation increase, which were confirmed by our results. However, without future climatic data from the existing climate models, the result of Yu et al. (2011) is only a primary projection, even though it is suitable for performing sensitivity tests of forest to climate change (Shao et al., 2003), and its reference value for practical application is reduced.

However, the results presented here should be interpreted with caution because some uncertainties in the PRECIS model and SRES scenario, a common phenomenon in climate impact assessment (New and Hulme, 2000). In addition, the future environment for tree growth will change greatly with the increases in the CO_2 concentration and the shifting pattern of temperature and precipitation, resulting in the self-adaptive behavior of the trees to the environment and changes in the growth–climate relationship.

5. Conclusion

Although the climate on Changbai Mountain, the main distribution area of Korean pine, is comparatively moderate and humid, the precipitation is also a limiting factor for the radial growth of Korean pine, particularly at low elevations. The specific growth–climate relationship is elevation dependent in addition to being species dependent. Under the projected future climate, the radial growth will increase with increases in the elevation and/or precipitation. Therefore, to adapt to climate change and improve the volume of Korean pine, the afforestation of this species should be in the higher elevation areas of the Korean pine's vertical distribution belt, which would be advantageous to forest management.

Acknowledgements

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