J. For. Res. (2017) 28(1):105–114
DOI 10.1007/s11676-016-0292-4

ORIGINAL PAPER

Relationships between tree-ring cell features of *Pinus koraiensis* and climate factors in the Changbai Mountains, Northeastern China

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Received: 18 March 2015 / Accepted: 27 October 2015 / Published online: 29 June 2016

Abstract Anatomical characteristics have been proven useful for extracting climatic signals. To examine the climatic signals recorded by tree-ring cell features in the Changbai Mountains, we measured cell number and cell lumen diameter, in addition to ring widths, of Korean pine (*Pinus koraiensis*) tree rings at sites of varied elevation, and we developed chronologies of cell number (CN), mean lumen diameter (MLD), maximum lumen diameter (MAXLD) and tree-ring width (TRW). The chronologies were correlated with climatic factors monthly mean temperature and the sum of precipitation. As shown by our analysis, the cell parameter chronologies were suitable for dendroclimatology studies. CN and TRW shared relatively similar climatic signals which differed from MLD and MAXLD, and growth-climate relationships were elevation-dependent, as shown by the following findings: (1) at each elevation, MLD and MAXLD recorded different monthly climatic signals from those recorded by TRW for the same climatic factors; and (2) MLD and MAXLD recorded climatic factors that were absent from TRW at lower and middle elevations. Cell lumen diameter proved to be an effective archive for improving the climate reconstruction for this study area.

Keywords Climate variability · Cell features · *Pinus koraiensis* · Dendroclimatology · Growth-climate relationships

Introduction

Tree rings are known to be a useful archive for studying climate variability (Esper et al. 2002; Cook et al. 2004). The dendroclimatology method uses tree-ring variables to examine radial growth-climate relationships by correlation analysis (Fritts 1974; Gagen et al. 2006; Lebourgeois et al. 2012). Ring width, because it easily can be measured and cross-dated, has widely been used as a climate proxy since tree-ring dendrochronology principles and methods were first established (Fritts 1976). Tree-ring width is a measure of the sum of a growing season's cell division and cell enlargement. The width of rings is primarily a function of three basic growth processes, viz. cell division, cell enlargement and cell differentiation (Vaganov et al. 2006). Thus, anatomical features such as cell number, cell size and cell wall thickness may carry higher-resolution climatic information than ring widths (Kirdyanov et al. 2003; Panyushkina et al. 2003) and therefore are of importance in examining growth-climate relationships.

Project founding: This research was supported by the National Science-Technology Support Plan Projects (2012BAC19B02) and the Beijing Natural Science Foundation Projects (8154046).

The online version is available at http://www.springerlink.com

Corresponding editor: Chai Ruihai

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The use of cell features in dendroclimatology is strongly related to the development of the applicable acquisition methods (Fonti et al. 2010). Initially, researchers used field monitoring to record changes in cell features and climate over a given period to analyze the relationships between cell features and climate (Knigge and Schulz 1961; Fritts 1966; Denne 1974; Ford et al. 1978; Antonova and Stasova 1993; Camarero et al. 1998). With the development of computerized image-analysis systems, more tree growth-climate relationships were investigated at the cellular scale (Yasue et al. 2000; Wang et al. 2002; Kirdyanov et al. 2003; Eilmann et al. 2006, 2009; Drew et al. 2012; Olano et al. 2012; Noval et al. 2013). In China, some studies attempted to examine the climatic information carried by the cell features of tree rings (Li et al. 2008; Wang et al. 2011; Xu et al. 2015). All of these studies reported that the cell feature variables carried more climatic information than did ring widths. Dendroclimatology studies using cell anatomical characteristics are in their initial developmental stages in China but have bright prospects.

The Changbai Mountains, a region in northeastern China where climate warming became obvious early on with a warming rate of about 0.3 °C $(10a)^{-1}$ (Guo et al. 2005; Dong and Wu 2007; Zhao et al. 2009), are of importance in climate reconstructions for China. They include a large area of undisturbed temperate old-growth forests (Shao and Zhao 1998). Korean pine (*Pinus koraiensis*) is the main coniferous species in the Changbai Mountains and many tree-ring studies have reported ring widths of *P. koraiensis* for this area (Shao and Wu 1997; Zhu et al. 2009; Gao et al. 2011; Yu et al. 2011; Wang et al. 2013). These studies concluded that temperature is the main climatic factor limiting radial growth. One study based on cell feature variables found that cell size carried a more strongly correlated precipitation signal than ring-width (Wang et al. 2011). Additionally, elevation is one of the main factors to affect tree radial growth, and many dendroclimatology studies have reported that tree growth-climate relationships were affected by or strongly dependent on elevation (Brookhouse and Bi 2009; Zhang et al. 2012). The Changbai Mountains are characterized by vertical vegetation zonation (Editorial Committee for Forestry of Jilin 1988; Hao et al. 2007). Previous studies found that growth-climate relationships were elevation dependent for *Larix olgensis* (Yu et al. 2005; Chen et al. 2011) and *Picea jezoensis* (Yu et al. 2006), the other two dominant coniferous species in the Changbai Mountains. Korean pine might also have an elevation-dependent growth-climate relationship.

Therefore, we examined Korean pine tree-ring samples from various elevations of the Changbai Mountains to (1) identify the consistent climatic signals contained in cell parameter chronologies and (2) quantify the effect of elevation on tree-growth relationships indicated by cell parameters.

Materials and methods

Study area and sampling sites

Our study area was on the northern slope of Changbai Mountain National Nature Reserve in northeastern China, in Jilin Province (42° to 42°45′E, 127°30′ to 128°30′N). The area attains its highest elevation of 2189 m above sea level (asl) at Tianchi Lake (Fig. 1). This area has not been extensively affected by anthropogenic activity, because Changbai Mountain did not become a tourist attraction until in the 1980s and was then designated a protected nature reserve (Yu et al. 2012). This area is characterized by a temperate continental monsoon climate (Editorial Committee for Forestry of Jilin 1988). Based on the average meteorological data from the Donggang and Erdao stations (data from the National Meteorological Information Center of China, Fig. 1), the mean annual temperature was 3.7 °C, with a mean temperature of 15.6 °C in January and 20.1 °C in July during the period 1971–2000 (Fig. 2). Mean annual precipitation was 811 mm, and mainly occurred from May to September. The vegetation of the area showed typical vertical zonation. Korean pine and broad-leaved mixed forest extended from 500 to 1100 m asl. A spruce-fir forest continued from 1100 to 1800 m asl. Soils in the coniferous forest zone are mountainous brown forest soil (Editorial Committee for Forestry of Jilin 1988).

Tree-ring cores were sampled from three sites designated Site 1, Site 2 and Site 3 (Fig. 1) at three elevations (Table 1). Site 1 and Site 2 were located at the lower and upper elevational range of distribution of Korean pine and broad-leaved mixed forest, respectively. Site 3, at 1258 m asl, sampled spruce-fir forest. All sites were located on a north-facing slope of 0–10. Approximately 30 of the largest and presumably oldest trees were selected at each site for sampling. Using increment borers two cores were extracted at breast height from each tree.

Laboratory work and chronology development

All cores were air-dried and then mounted and sanded to produce clearly visible tree-ring boundaries. They were visually cross-dated (Stokes and Smiley 1968) under stereoscopes. Total ring width was measured using a LINTAB-station (Frank Rinn, Heidelberg, Germany) at 0.01 mm resolution. The COFECHA program (Holmes 1983) was used to check the quality of cross-dating and measurements. Based on the statistics from COFECHA, only individual samples with consecutive segments that

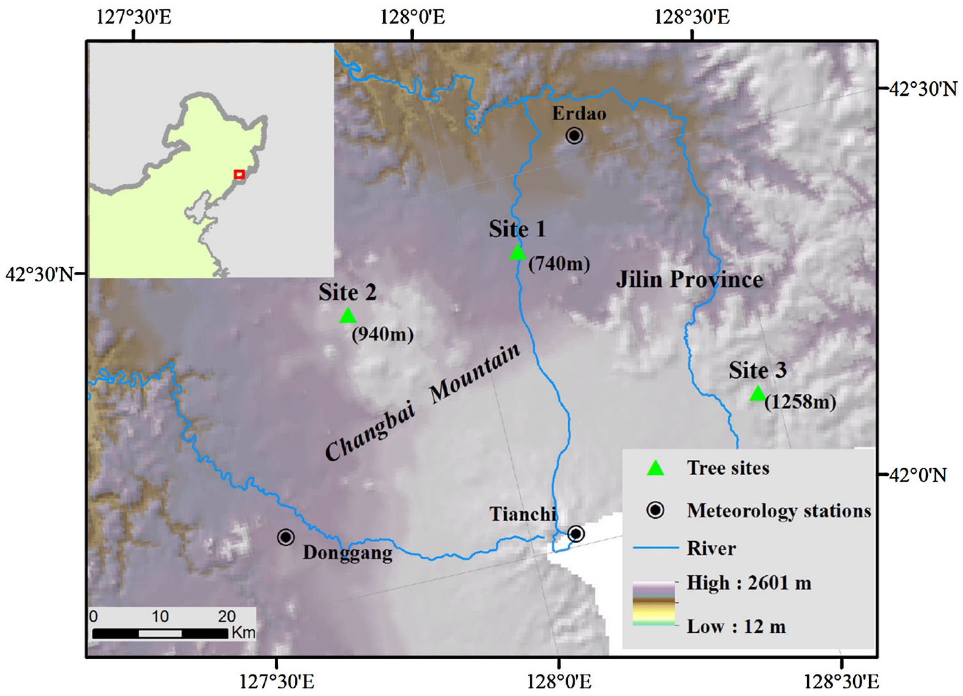

Fig. 1 Locations of tree-ring sampling sites and meteorological stations in the study area

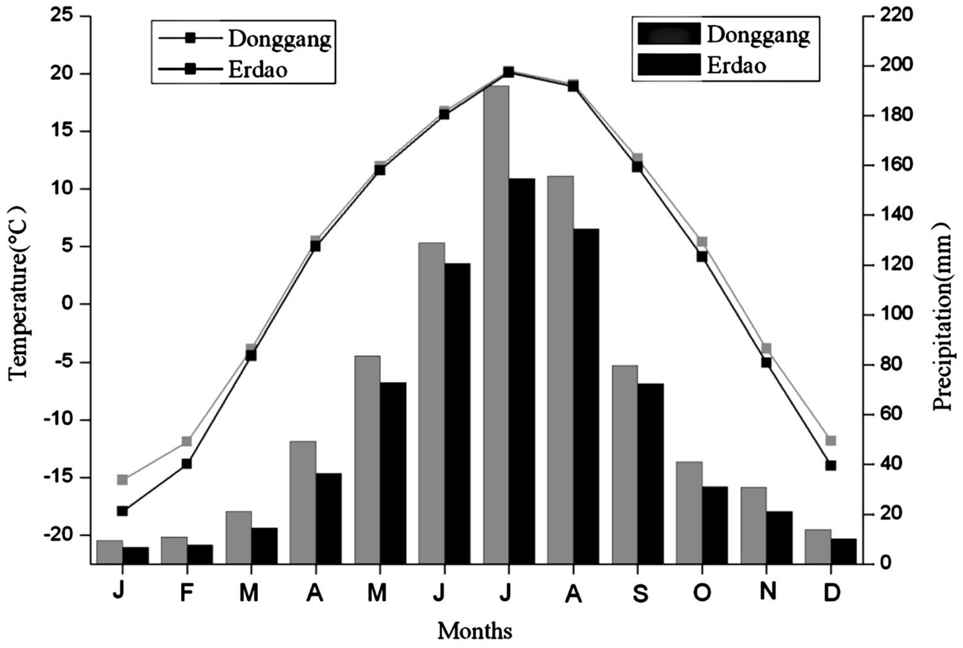

Fig. 2 Long-term monthly mean temperature (*line/squares*) and precipitation (*bars*) at the Donggang and Erdao stations, based on data for the period 1971–2000

Table 1 Geographic locations and sampling information for Sites 1, 2 and 3

Site name	Latitude (N)	Longitude (E)	Elevation (m)	Slope	Trees/cores
Site 1	42.4°	128.1°	740	0–5°	32/65
Site 2	42.37°	127.77°	940	10°	29/59
Site 3	42.15°	128.47°	1258	0–5°	29/58

correlated well with the master series and had high sensitivity were included in development of cell parameter chronologies. Twelve to 15 cores of different trees were selected for cell parameters measurements. The number of samples was sufficient to obtain credible cell features (Fonti et al. 2009). These cores were further polished to make cell boundaries clearly visible for identification. We used the MIVNT image analysis system (Guilin, Guangxi, China) to measure cell number and cell lumen diameter. The software is widely used to process and analyze images in various fields, such as material science, biology and chemistry. Cell numbers and lumen diameters were measured along each of five radial files of each growth ring. To allow direct comparisons of cell dimensions patterns between rings with different cell numbers, we converted all size measurement series to the average numbers of all annual rings using the method of Vaganov (1990). The cell variable values were averaged within each tree ring to develop chronologies.

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 age-related growth trends of raw ring-width chronologies and cell number chronologies. Lumen diameter chronologies have no obvious long-term growth trends; therefore, they were standardized using straight lines ((value-mean)/mean) (Conkey 1986). The resulting ratio series was then computed as a biweight robust mean of the detrended and standardized individual series (Cook et al. 1990). Finally, the chronologies of ring-width (TRW), cell number (CN), maximum lumen diameter (MAXLD) and mean lumen diameter (MLD) were constructed. To show the strength of common signals in the chronologies, we performed a within-chronology common interval analysis for each chronology. The statistical quality of each chronology was measured using several coefficients commonly used in dendrochronology, including standard deviation (SD), mean sensitivity (MS), first-order autocorrelation (AC1), mean correlation between trees (R), variance in the first principal component (PC1) (Fritts 1976) and the expressed population signal (EPS) (Wigley et al. 1984). The EPS indicates the chronology confidence level (Briffa and Jones 1990), and a threshold value of 0.85 is often used to evaluate the useful time span of the final chronologies (Wigley et al. 1984). Three types of chronologies (residual, standard or arstan) were established (Cook and Holmes 1986), and the standard chronologies were used to analzye growth-climate relationships. To measure the similarity between any two chronologies, we used Pearson correlation analysis and principal component analysis for the common time span from 1958 to 2002.

Climatic data

Climatic data were obtained from the Erdao (591 m asl), Donggang (774 m asl) and Tianchi (2623 m asl) meteorological stations near the sites in the study area (Fig. 1). The Tianchi station data were not used because winter observations were terminated in 1989. The monthly mean temperature and precipitation correlation coefficients of Erdao and Donggang stations in corresponding months from 1958 to 2007 were 0.95 and 0.79, respectively. Therefore, we averaged the meteorological data from the Erdao and Donggang stations to improve the regional representation, and we used the average values to analyze the growth-climate relationships.

Analysis of tree growth-climate relationships

Pearson correlation analysis was used to identify the growth-climate relationship (Fritts 1974). Because the width of an annual ring can be affected by climatic conditions over a long period, the climatic conditions in the prior year may affect the growth in the current year (Fritts 1976). Thus, the monthly mean temperature and total precipitation from the prior September to the current August were included in the analysis. Meteorological data were limited from 1958 to 2007, therefore we analyzed the growth-climate relationship for the period 1959–2007 at Site 1 and Site 3 and for the period 1959–2002 at Site 2.

Results

Chronology characteristics

The statistics of the cell chronologies of each site were lower in value than were those for the TRW, especially for MLD and MAXLD (Table 2). The SD and MS values, which indicate the dispersion degree of indices and the annual variability, respectively, were especially low.

The characteristics of the chronology changed with elevation. MS, SD and EPS were highest for the Korean pine chronology at Site 1 and smallest at Site 2. The result means that the annual variability of ring variables and the population signal of the sample declined with increasing elevation. The AC1 of the chronologies at Site 2, was lowest, particularly for the MAXLD, and there were fewer common signals at Site 2 chronologies with lower R and PC1.

The annual variation of indices revealed the correlations between the chronologies of each variable (Fig. 3). Synchronous behavior of the variables at Sites 1 and 2 was visible in specific pointer years (e.g., 1965, 1974, 1975, 1983, 1990 and 1994). The correlation coefficients shown in Table 3 illustrated this phenomenon. The correlation coefficients of the chronologies for every variable except MAXLD were greater than 0.439 ($P < 0.01$) at Sites 1 and 2. The similarities between Site 3 and the other two sites were very low for all variables, except for the correlation

Table 2 Standard chronology statistics and common period analysis results for each variable of Korean pine (*Pinus koraiensis*) at Sites 1, 2 and 3

	TRW			CN			MLD			MAXLD		
	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3
MS	0.20	0.17	0.12	0.17	0.16	0.11	0.05	0.04	0.03	0.04	0.03	0.03
SD	0.21	0.16	0.16	0.19	0.15	0.15	0.04	0.03	0.03	0.04	0.03	0.03
AC1	0.30	0.11	0.59	0.33	0.15	0.58	0.13	−0.12	0.33	0.12	0	0.25
R	0.49	0.40	0.43	0.48	0.39	0.41	0.25	0.25	0.17	0.19	0.13	0.15
EPS	0.93	0.91	0.90	0.93	0.91	0.89	0.83	0.83	0.71	0.76	0.69	0.68
PC1/%	53.3	44.6	48.6	51.4	43.9	46.4	31.9	32.5	27.4	26.1	26.6	23.7

TRW ring width, *CN* cell number, *MLD* mean lumen diameter, *MAXLD* maximum lumen diameter, *SD* standard deviation, *MS* mean sensitivity, *AC1* first-order autocorrelation, *R* mean correlation between trees, *PC1* variance in the first principal component, *EPS* expressed population signal

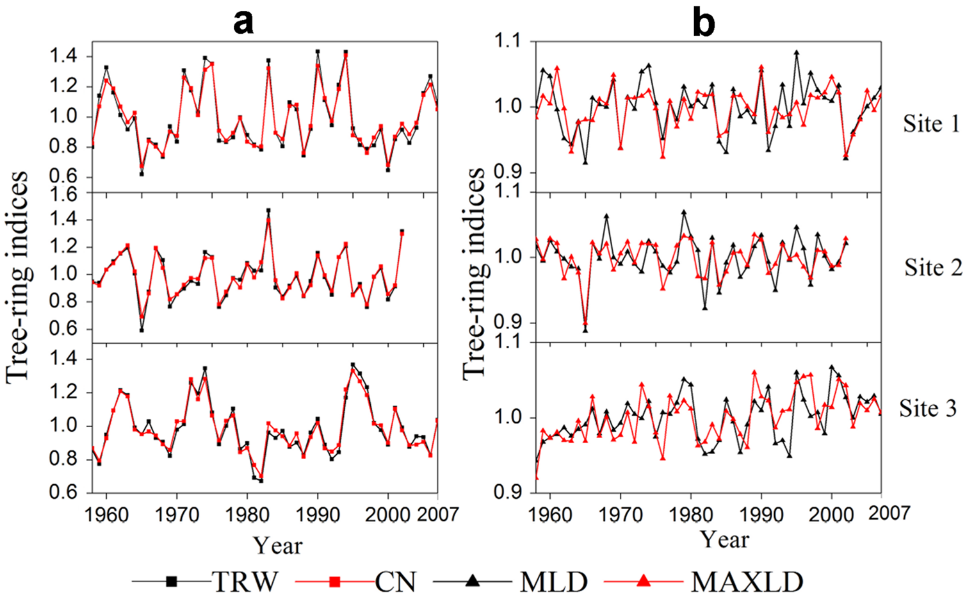

Fig. 3 Annual variations of ring width (TRW), cell number (CN), mean lumen diameter (MLD) and maximum lumen diameter (MAXLD) during 1958–2007 for Sites 1 and 3 and during 1958–2002 for Site 2

Table 3 Correlations between chronologies of four variables for Korean pine (*Pinus koraiensis*) between Site 1, 2 and 3

	TRW	CN	MLD	MAXLD
Site 1–Site 2	0.54 ($P < 0.01$)	0.55 ($P < 0.01$)	0.44 ($P < 0.01$)	0.18
Site 1–Site 3	0.21	0.26	0.09	0.10
Site 2–Site 3	0.12	0.15	0.32 ($P < 0.05$)	0.27

coefficient of MLD between Sites 2 and 3, which was 0.321 ($P < 0.05$).

The chronologies of all variables were compared at each site to determine whether they contained the same kind of information (Table 4). Generally, TRW and CN were very closely related, displaying a correlation higher than 0.96 ($P < 0.01$) at all three sites. The correlations were also high between MLD and MAXLD with the value higher than 0.60 ($P < 0.01$). However, the correlations were lower between cell size chronologies and TRW or CN, although some were significant. This result can be best expressed by principal component analysis at each site (Fig. 4), which sorts the variables according to their correlations. The two first principal components retained more than 90 % of the total variance. Ordinations along the two axes all showed that TRW and CN were significantly different from the two cell size variables.

Table 4 Correlations among chronologies of *Pinus koraiensis* tree-ring variables

	TRW	CN	MLD
Site 1			
TRW	–	–	–
CN	0.96 ($P < 0.01$)	–	–
MLD	0.33 ($P < 0.05$)	0.23	
MAXLD	0.27	0.21	0.73 ($P < 0.01$)
Site 2			
TRW	–	–	–
CN	0.98 ($P < 0.01$)	–	–
MLD	0.46 ($P < 0.01$)	0.33 ($P < 0.05$)	–
MAXLD	0.55 ($P < 0.01$)	0.47 ($P < 0.01$)	0.76 ($P < 0.01$)
Site 3			
TRW	–	–	–
CN	0.98 ($P < 0.01$)	–	–
MLD	0.24	0.13	–
MAXLD	0.39 ($P < 0.01$)	0.30 ($P < 0.05$)	0.60 ($P < 0.01$)

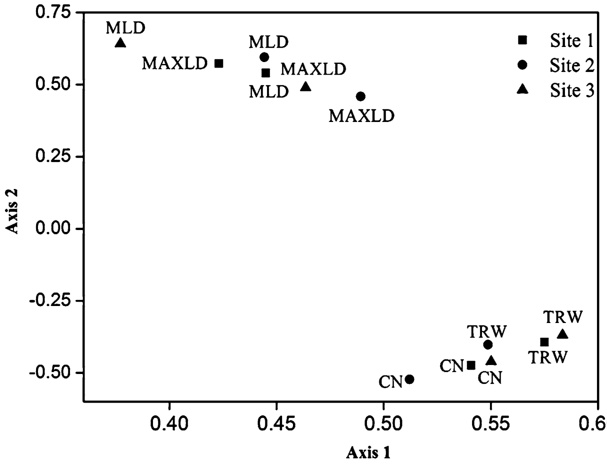

Fig. 4 Scatter plots of principal component analysis loading of the four chronologies of each site for *Pinus koraiensis* plotted along the axes of the two first principal components (the two first principal components retained more than 90 % of the total variance)

Relationships between cell variable chronologies and climatic factors

Climatic signals recorded by cell lumen diameters

MLD and MAXLD were correlated with monthly mean temperature and the sum of precipitation (Fig. 5). At Site 1, MLD was positively correlated with March temperature while MAXLD was not. Both of these chronologies were negatively and significantly correlated with May temperature. MLD and MAXLD were both positively correlated with precipitation in May, and MLD was highly correlated with June precipitation in the current year. MLD and MAXLD were positively correlated with March temperature and June precipitation at Site 2; additionally, MLD at this site was positively correlated with July precipitation. At the highest elevation, MLD and MAXLD only reflected the temperature signal and were positively correlated with the previous October or current June temperatures.

Comparison of the growth-climate relationship for cell variables and ring widths

The relationships at each site between CN and climatic factors were similar to the relationships between TRW and climatic factors (Fig. 5). However, the relationships between lumen diameters or ring widths and climate factors revealed that lumen diameters can record different climatic signals from those recorded by ring widths.

At Site 1, TRW was not related to monthly temperature; it was positively correlated with precipitation in the previous September and in the current June. This result was different from that found for the precipitation signal recorded by MLD and MAXLD. At Site 2, TRW was positively correlated with April temperature, contrasting with the temperature signals recorded by MLD and MAXLD. TRW at this site was unrelated to precipitation. TRW at Site 3 was positively correlated with July temperature and precipitation during the previous September when there was no precipitation signal in MLD or MAXLD.

Discussion

Evaluation of the chronology characteristics of cell variables

The established chronology characteristics of the cell variables showed substantially lower sensitivities and common signals than did ring widths. This phenomenon was reported by others (Yasue et al. 2000; Wang et al. 2002; Corcuera et al. 2004). The common signal indicates the statistical quality of each chronology, so growth ring width is more suitable for dendroclimatology study. Ring width cannot, however, inform regarding analogies or differences in the ecological information that the chronology records. The identification of such information requires a comparison of the chronologies with each other and with climate data (Wimmer and Grabner 2000; Fonti and García-González 2004). Previous studies on the mean vessel area of ring-porous species showed mean sensitivities and correlations between samples ranging from 0.05 to 0.20 and from 0.2 to 0.4, respectively (Tardif and Conciatori 2006; Fonti et al. 2007). Nevertheless, the

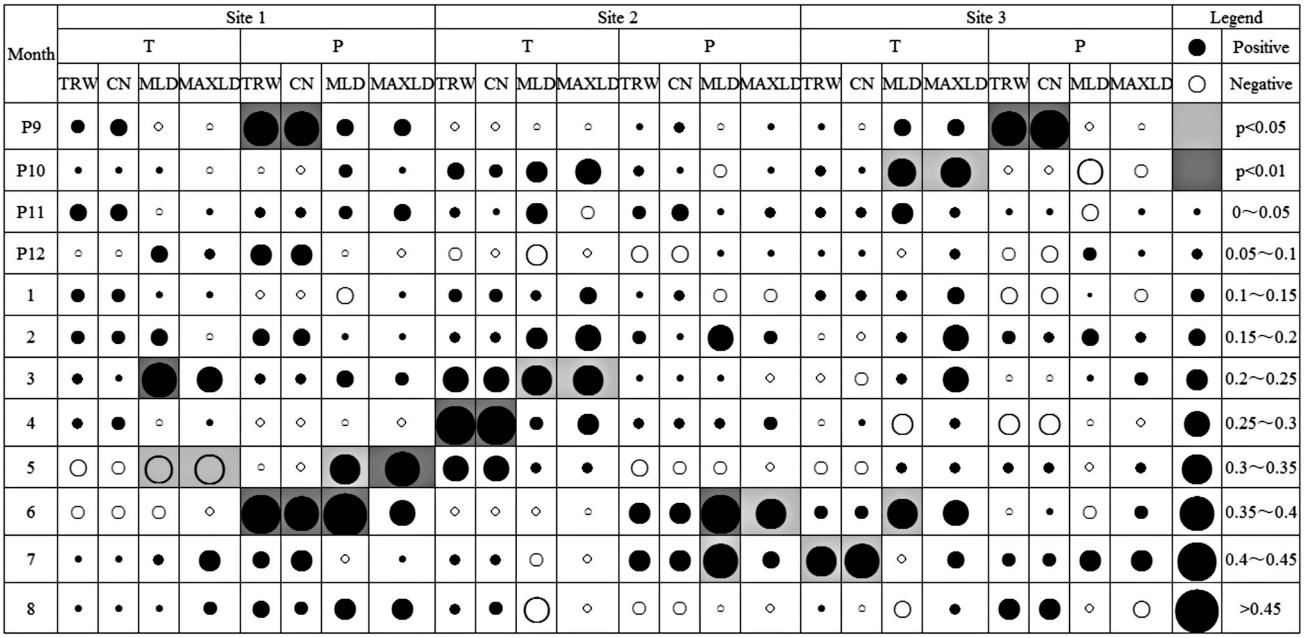

Fig. 5 Correlation coefficients between monthly climate elements and tree-ring indices during 1959–2007 for Sites 1 and 3 (1959–2002 for Site 2). Sizes of the circles indicate the strengths of the correlations. *P9* the previous September, *P10* the previous October, *P11* the previous November, *P12* the previous December, *T* temperature, *P* precipitation

correlations with climatic parameters reached values >0.60 in certain cases. For coniferous species, Yasue et al. (2000) found that the mean sensitivity and correlation between samples of *Picea glehnii* cell wall thickness were 0.05 and 0.14, respectively, but 37 % of the variance could be explained by climatic factors. Although the statistical quality of MLD was lower than that for TRW at Site 1 in our study, MLD was positively correlated with March and May temperature that could not be recorded by TRW. Similar results were recorded for Sites 2 and 3. In order to improve the statistical quality of cell variables, we suggest to increase sample sizes. For example, when the sample size of MLD at Site 1 increased to 16 cores, EPS improved to 0.85.

The chronologies of TRW and CN showed almost the same relationships with climatic factors at all three elevations. This suggests that TRW was correlated with CN, meaning that ring width depended primarily on cell numbers, a common phenomenon in coniferous species. Camarero et al. (1998) reported that the ring widths and cell numbers of *Pinus uncinata Ram.* and *Pinus sylvestris L.* in the Central Spanish Pyrenees were functionally correlated ($P < 0.001$). The correlation coefficient of these two variable chronologies was 0.78 for *Larix cajanderi.* ($P < 0.05$), as calculated by Panyushkina et al. (2003), and 0.907 for *Picea crassifolia* ($P < 0.01$), as calculated by Li et al. (2008). This phenomenon can be attributed to the processes governing cell anatomy; Cuny et al. (2012) monitored the intra-annual wood formation dynamics of three coniferous species and estimated that approximately 75 % of the annual radial increment variability was attributable to the rate of cell production, whereas only 25 % was attributable to its duration. For this reason, cell number has been used relatively infrequently to analyze the growth-climate relationship (Deslauriers and Morin 2005).

Limiting climatic factors for the radial growth of Korean pine at different elevations

The combination of the relationships between cell variables/ring widths and climatic factors showed that both temperature and precipitation were limiting factors for the radial growth of Korean pine in the study area.

March temperature and previous September precipitation were the common climatic factors limiting tree growth at all three sites. MLD was positively correlated with March temperature because a high temperature before the growing season can promote cambial activity and can improve photosynthesis, both of which are positively related to cell enlargement. Greater precipitation in September leads to greater soil-moisture availability and this is advantageous to Korean pine growth in the following year.

The low correlations of each variable chronology between sites (Table 3) indicated that there were also differences in the growth-climate relationship related to elevation. At the low elevation site, TRW was also limited by precipitation in the current June. This finding is consistent with the results of Yu et al. (2011). MLD and MAXLD can record May precipitation because the largest cells are formed during the early growing season and these are a more reliable proxy for climatic conditions during that period than is TRW. At the middle elevation site, MLD and MAXLD correlated well with June precipitation, complementing the climatic signals furnished by TRW. At the high elevation site, July temperature was the limiting factor for ring width. This finding verifies the conclusion of Gao et al. (2011). With increasing elevation, lower temperatures can delay the onset of the growth period and terminate growth before the end of the growing season at lower elevations. MLD at this elevation was significantly correlated with June temperature. This verified that cell lumen diameter can record climate factors for earlier months. Nevertheless, at high elevation, lumen diameter chronologies did not respond significantly to the precipitation signal. The reason for this outcome might be the increase in precipitation at this elevation.

Since the MLD and MAXLD supplied different climatic information from that yielded by TRW, they can improve climate reconstruction in the Changbai Mountains. However, because the climatic data used to analyze the growth-climate relationships were expressed on a monthly basis, it cannot be determined whether lumen diameters in this area can offer a higher temporal resolution than ring widths. In further studies, climatic data at a scale of days or pentads should be used to examine the climatic signals recorded by cell features. Additionally, mechanistic models such as TREERING (Fritts et al. 1999), which uses daily climatic data to simulate processes affecting the formation of cell features, may be effective methods for studying the growth-climate relationship at the cellular scale.

Conclusions

It is possible to build variable chronologies for cells of Korean pine in the Changbai Mountains for dendroclimatology studies. Although the statistics of the cell lumen diameter chronologies were lower in value than the statistics of the ring-width chronologies, they can record different climatic signals from those encoded in ring widths. Both temperature and precipitation are limiting factors for Korean pine radial growth, and the growth-climate relationships change with elevation. The significance of cell features in reconstruction of spring temperature at low elevation, summer precipitation at middle elevation, and autumn temperature at high elevation of the Changbai Mountains has been demonstrated, but the relationship between cell features and climate should be further investigated to assess the climatic reconstruction potential offered by cell features.

Acknowledgments This research was supported by the National Science-Technology Support Plan Projects (2012BAC19B02) and the Beijing Natural Science Foundation Projects (8154046).

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