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ORIGINAL PAPER

Age-independent climate-growth response of Chinese pine (*Pinus tabulaeformis* Carrière) in North China

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Abstract

Key message **This manuscript describes the characteristics and climate-growth responses of Chinese pine in different age classes; and determines the climate-growth response of Chinese pine in North China is age independent.**

Abstract The Chinese pine (*Pinus tabulaeformis* Carrière) is a widespread conifer species in North China and has been widely used in dendrochronology studies. In this research, tree-ring samples of the Chinese pine in North China were investigated based on three age classes, 70–120, 121–170, and 171–220 years old, in one sampling site. The environment of the sampling site was properly considered and other potential influences were avoided as far as possible to highlight the possible influences of age on the climate-growth response of the trees. The individual tree-ring index series showed generally consistent variation trends with the first principal component series of the total tree-ring indices. They varied independently of their age class and showed no significant group difference during their common period from 1940 to 2009. The annual variations of the three age-class chronologies were synchronous, and the characteristics of the individual tree-ring width chronology were also analyzed. Correlation function analyses indicated that all of the chronologies have similar responses to climate. The climate-growth response of Chinese pine in North China is age independent in the three age classes. In addition, more extensive studies with larger geographic scales and more species are required in North China.

Keywords Chinese pine · Tree ring · Climate-growth response · Age independent · North China

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Introduction

Tree rings are valuable sources of information. They have been widely used in paleoclimatic studies because of their ability to record environmental signals during formation, and they provide important proxy data for paleoclimatic studies. The greatest strength of tree ring is that it has an annual resolution with a high degree of confidence. Dendroclimatology is a particularly appropriate discipline for the study of historical climate fluctuations. Numerous long historical climate series have been reconstructed based on tree-ring data (Esper et al. 2002; Mann and Jones 2003; Bräuning and Mantwill 2004; Sheppard et al. 2004; D'Arrigo et al. 2006; Treydte et al. 2006; Buckley et al. 2007; Briffa et al. 2008; Yadav et al. 2011; Cook et al. 2013). The use of dendroclimatology in China has progresses recently, and some century to millennia-long precipitation, temperature, runoff, and drought reconstructions have been developed (Zhang et al. 2003, 2009, 2013b; Shao et al. 2005; Yu et al. 2006; Gou et al. 2007; Yuan et al. 2007; Liang et al. 2009; Liu et al. 2009, 2013; Wang et al. 2009; Fan et al. 2010; Wang et al. 2010; Chen et al. 2011; Zhu et al. 2011; Bao et al. 2012; Yang et al. 2012; Li et al. 2013).

The physiological mechanisms used to identify climatic parameters in tree rings are complex, because a tree ring in any given year integrates the effects of both climatic variables and biological growth functions, which are influenced by endogenous and exogenous factors (Fritts 1976; Szeicz and MacDonald 1994). In dendroclimatology analyses, there is an expectation that tree-ring-recorded climate signals could be maximized; therefore, the non-climatic effects recorded during the tree growth are usually removed by standardization (Linderholm and Linderholm 2004). Based on the uniformitarian principle, which states that the mechanisms linking tree-ring growth to climate conditions remain unaltered over time, it is generally assumed that the relationships between the radial growth of the tree and climate are age independent once the non-climatic effects have been removed (Szeicz and MacDonald 1994; Hughes 2002; Carrer and Urbinati 2004; Rossi et al. 2008). Therefore, trees with different ages will have uniform responses to climate.

In recent years, ecophysiological studies have demonstrated that the physiological processes in young and old trees are different, such as lower photosynthetic rates in older trees as have been measured in various conifer species (Bond 2000). This indicates that growth-related climate signals are likely to be age dependent, which would directly lead to biased climate reconstructions based on even-aged samples. Therefore, a number of dendrochronological studies have focused on the age-dependent response differences between tree-ring growth and climate. Until now, age-dependent climate response studies have provided ambiguous results, with some studies indicating that there are age effects on climate signals (e.g., Szeicz and MacDonald 1994; Ogle et al. 2000; Carrer and Urbinati 2004; Linderholm and Linderholm 2004; Rozas 2005; Esper et al. 2008; Vieira et al. 2009; Schuster and Oberhuber 2013) and others showing that climate-growth responses are age independent (e.g., Fritts 1976; Kirkpatrick 1981; Colenutt and Luckman 1991, 1995; Wilson and Elling 2004).

The limited number age-dependent climate response studies developed in China have also produced ambiguous results (Yu et al. 2008; Wang et al. 2009, 2011; Zhang et al. 2013a; Wu et al. 2013). Yu et al. (2008) compared different age classes of *Sabina przewalskii* Kom. in the Qinghai–Tibetan Plateau. The results showed that the mean sensitivity and standard deviation of the tree-ring series did not change significantly with age; however, the radial growths of older trees were shown to be more sensitive to climate change than those of younger trees. Wang et al. (2009) found that the mean sensitivity and standard deviation of tree-ring widths for *Larix gmelinii* <150 years old increased with age, whereas they had no significant relationship with age in trees >150 years old; trees <150 years old responded differently to climate than trees >150 years old in northeastern China. Wu et al. (2013) found that younger *Picea schrenkiana* were more sensitive to climate than the older trees in the western area of the Tianshan Mountains.

Chinese pine (*Pinus tabulaeformis* Carrière) is an endemic and widespread conifer species in northern China and has been widely used in dendrochronology studies in China (Li et al. 2007; Liang et al. 2007; Fang et al. 2010; Liu et al. 2010, 2012; Shi et al. 2008; Song and Liu 2011; Li et al. 2011; Cai et al. 2010). Zhang et al. (2013a) analyzed the Chinese pine in different age classes in the Qilian Mountains, northeast Tibetan Plateau and found that there were differences in the climate response between the young and old trees. Until now, analyses have not been performed for the relationship difference between climate and the growth of Chinese pine in different age classes in North China, and the question of whether the climate-growth response of Chinese pine in North China is age independent has not been resolved. In this paper, we analyzed the characteristics of Chinese pine in different age classes in North China, including mean sensitivity (MS), standard deviation (SD), signal-to-noise ratio (SNR), expressed population signal (EPS), variation in first principal component (PC1), and so on. The consistency of the annual tree growth of the samples was examined. The annual variations of the chronologies in different age classes and the relationships between the chronologies and climate were compared to determine whether the climate-growth response of Chinese pine in North China is age independent.

Materials and methods

Study area and tree-ring chronology

The study area is the Guancen Mountains, which are located in the eastern part of the Loess Plateau, North China (Fig. 1). The Guancen Mountains have comparatively abundant forest resources, and the dominant tree species is Chinese pine, which is followed by larch (*Larix gmelinii*). The study area is located in the temperate continental climate region, the annual precipitation is approximately 430 mm, and the average temperature is approximately 9 °C. The samples were collected in the northern Guancen Mountains.

Some researches demonstrated there were some potential factors, such as crown, affecting the differences among age classes. Carrer and Urbinati (2004) found that the age effect in tree-ring parameters was clear in *Larix decidua* than in *Pinus cembra* and explained this may partly attribute to the different patterns observed in tree height and

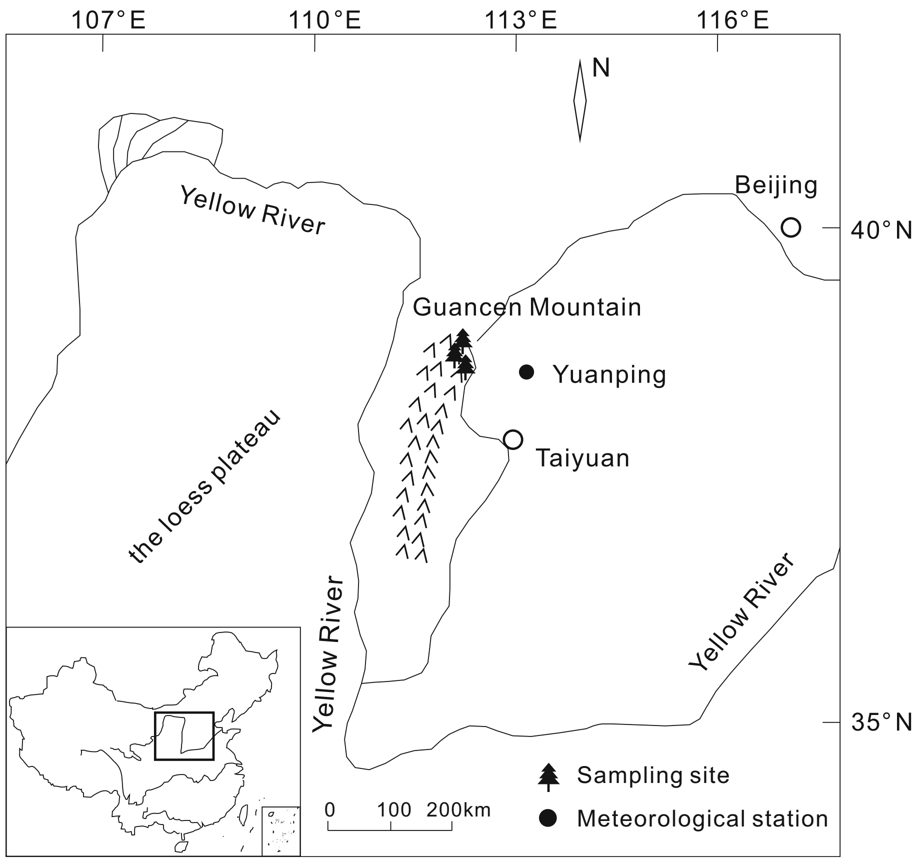

Fig. 1 Locations of the sampling sites and Yuanping meteorological station

age relationships. Pichler and Oberhuber (2007) indicated that the understory trees experienced greater growth reductions during droughts than overstory ones in *Pinus sylvestris* in an inner Alpine environment. Martín-Benito et al. (2008) showed that the dominant trees of *Pinus nigra* reduced growth during the drought more than suppressed trees but also recovered faster afterward in a Mediterranean climate. Therefore, the environment of the sampling site should be properly considered. Indeed, it is hard to get an ideal sampling site, excluding all the other potential factors affecting differences among age classes, in the field work. To highlight the possible influences of age on the climate-growth response of the trees in the study area, the potential factors (e.g., longitude and latitude, altitude, crown competition, and tree species) were avoided as far as possible in sampling. The samples were collected between 38°42′14″ and 38°42′33″N and between 111°57′44 and 111°58′28″E at an elevation between 1,700 and 1,900 m a.s.l. All of the sampled trees grew under relatively scattered conditions in a homogeneous microenvironment of thin soil and scattered shrubs and grasses in the understory, and there was no apparent anthropogenic influence. All increment cores were collected from Chinese pine of 7–9 m high. For each tree, two cores were taken at breast height (BH). Diameter at BH of the sampled trees mainly concentrated on 25–35 cm. In total, 136 cores were collected at BH from 68 Chinese pine trees.

The samples were dried, mounted, surfaced with progressively finer grade sandpaper, and cross-dated. The samples were then measured with a precision of 0.01 mm (Stokes and Smiley 1996). The COFECHA program was used to control the quality of the cross-dating and measurements of the ring-width series in the three age classes (Holmes, 1983). For the cores that had no pith but were near the pith, 2–7 rings were added to estimate their age after comparing their ring patterns with the cores that had pith (Clack and Hallgren 2004). The age of the shorter core was dated by the longer one of the same tree. Some cores were far away from the pith and were excluded from the final samples. In addition, a common time span and the same number of samples in different age classes should also be taken into account for making comparable statistics. Considering the age range of the samples and reasonable sample size of the various age classes, 108 cores from 54 trees (between 70 and 220 years old) were finally involved. All the samples were grouped into three age classes based on the tree age at BH and every class included 36 cores from 18 trees. Age class one (AC1) included the young trees at 70–120 years old. Age class two (AC2) included the middle-age trees at 121–170 years

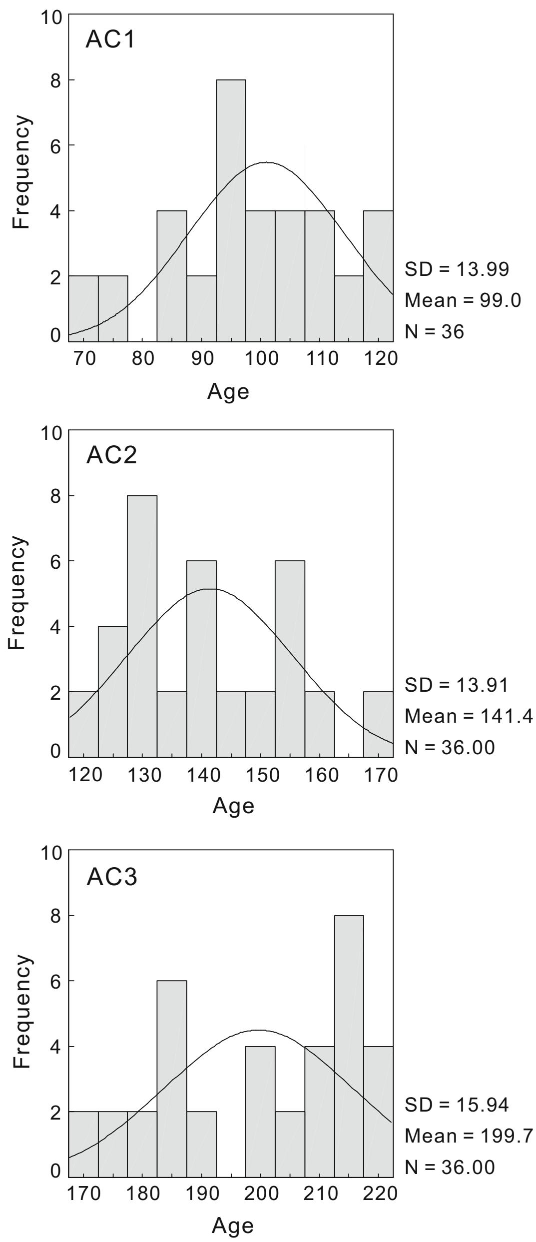

Fig. 2 The mean age, standard deviation (SD), and frequency distribution of the tree ages in the age class 1 (AC1), age class 2 (AC2), and age class 3 (AC3). *N* indicates the number of cores in every age class

old. Age class three (AC3) included the old trees at 171–220 years old. Figure 2 shows the mean, SD, and frequency distribution of the tree age in the three age classes.

Each individual raw ring-width measurement series was detrended and standardized to ring-width index using the program ARSTAN (Version 44h3, http://www.ldeo.columbia.edu/tree-ring-laboratory/resources/software). Undesirable growth trends unrelated to climatic variations were removed from each series during the detrending process. The conservative method, negative exponential curve or a straight line, was employed to fit each ring-width measurement series. The ARSTAN program can build three kinds of chronologies, standard (STD) chronology, residual (RES) chronology, and ARSTAN (ARS) chronology. The aim of this research was to determine whether the climate-growth response of Chinese pine in North China is age independent by comparing the annual variations of the chronologies and the relationships between the chronologies and climate in different age classes. The RES chronology has more high frequency signals; therefore, the RES chronology was ultimately used in the climate-growth relationship analyses. The AC1 chronology, AC2 chronology, and AC3 chronology mentioned in this research referring to RES chronologies built based on the tree-ring width measurements of AC1, AC2, and AC3 groups.

Meteorological data

The Yuanping meteorological station is located at 112°43′E, 38°44′N, which is east of the sampling sites at 828 m a.s.l. The straight-line distance between the station and sites is approximately 50 km. Both the Yuanping meteorological station and our sampling sites are located east of the Guancen Mountains. Considering the similar climatic conditions within the study region, the local mean monthly temperature and total monthly precipitation records from the Yuanping meteorological station were used in this study (Fig. 1).

Statistical methods

To discern the growth characteristics and possible differences among the AC1, AC2, and AC3 chronologies, several commonly used descriptive statistics in dendrochronology were employed: MS, SD, SNR, EPS, PC1, mean correlation among all series, mean correlation between trees, and mean correlation within trees. MS and SD measure the relative change of the ring widths from one year to the next or the departure from the mean value. The SNR can quantify the potential signal in the chronology, whereas the EPS indicates the degree to which the particular sample chronology portrays a hypothetically perfect chronology (Fritts 1976; Wigley et al. 1984). PC1 and mean correlations can estimate the amount of year-to-year growth variances that occur among the samples in the chronology (Carrer and Urbinati 2004; Linderholm and Linderholm 2004; Wang et al. 2009).

The principal component analysis (PCA) is a standard multivariate technique that can compress data and reduce data dimensionality; therefore, the majority of variation can be accounted for using only a few explanatory variables and is analyzed more easily than the original dataset.

Table 1 Statistical characteristics of the chronologies of age class 1 (AC1), age class 2 (AC2), and age class 3 (AC3) in North China

	AC1	AC2	AC3
Number of cores	36	36	36
Mean sensitivity	0.33	0.31	0.39
Standard deviation	0.25	0.26	0.31
Mean correlation among all series	0.50	0.51	0.56
Mean correlation between trees	0.50	0.50	0.56
Mean correlation within trees	0.78	0.76	0.82
Signal-to-noise ratio	24.92	32.51	29.15
Year of expressed population signal >0.85	1915	1875	1825
Variation in first principal component	52.43 %	52.71 %	50.09 %

The PCA was applied to estimate the coherence of the series from different age classes.

The climate-growth relationships were investigated using correlation function analyses. Pearson's correlation coefficient, which is often used when measuring the influence of one time-dependent variable on another in climate time series, was employed to compare the response difference of the trees to climate in different age classes. DENDROCLIM 2002 software utilizes bootstrap confidence intervals to estimate the significance of correlation coefficients. It can accurately test the significance of correlation and without passing the erroneous significance (Biondi and Waikul 2004; Mudelsee 2003). In this paper, DENDROCLIM 2002 software was used for calculating the correlations between the tree-ring chronologies and climatic data.

Results and discussion

Tree-ring growth coherence

The raw ring-width measurements indicated that annual growth variations of the samples in the study region have high coherence during their common period from 1940 to 2009 (figure not shown). The series intercorrelations of the ring-width measurements in AC1, AC2, and AC3 were 0.71, 0.69, and 0.73, respectively; and it was 0.70 in the total 108 raw ring-width (TRW) measurements of the sampling site.

We summarized the chronology statistics in Table 1. As shown, the statistics in the age-class chronologies have common features. A slightly higher MS and SD occur in the old group. The mean correlations among all series, between trees, and within trees are also higher in the old group. All of the statistics convey approximate values in the three age classes.

Table 2 Correlation coefficients between the three age-class chronologies and mixed-age chronology (TRW) during their common period from 1915 to 2009 in North China

	AC1	AC2	AC3	TRW
AC1	1.00			
AC2	0.95	1.00		
AC3	0.91	0.88	1.00	
TRW	0.98	0.96	0.97	1.00

The TRW chronology was built by the total 108 raw ring-width measurements of the sampling site. All values are significant at the 99 % confidence level

The comparisons of the age-class chronologies during their common period (EPS >0.85) from 1915 to 2009 indicated that the growth patterns of the chronologies have synchronous annual variations (figure not shown). The correlations between the three chronologies range from $r = 0.88$ to $r = 0.95$ ($p < 0.0001$, $n = 95$). The age-class chronologies also have high coherence with the mixed-age chronology built from TRW series (TRW chronology) and their correlation coefficients range from $r = 0.96$ to $r = 0.98$ ($p < 0.0001$, $n = 95$) (Table 2). The significant correlation coefficients among these chronologies further confirmed their synchronous growth patterns.

A PCA was also used to estimate the common growth patterns of the three age-class chronologies and to determine whether the different age-class chronologies have a coherent signal. We selected the eigenvalues greater than 1 in extracting the components. One component was extracted. The first principal component has an eigenvalue of 94.34 % and explained 94.34 % of the variance. The first principal component explained the majority of the variances in the three age-class chronologies, which indicated that the three age-class chronologies have consistent information and have no age differences.

To more objectively estimate if the growth patterns of the series from different age classes stayed together within their groups or they spread around independently of their ages, all the individual tree-ring indices (after being standardized) were compared in Fig. 3. The upper, middle, and bottom part of Fig. 3 represent the individual tree-ring indices of AC1, AC2, and AC3, respectively. The first principal component series of the total 108 tree-ring indices was also shown as PC1-T in Fig. 3, which was for acquiring the common signal of the tree-growth pattern in study region and for examining whether the growth variations of the sampled trees are age independent. For better visual comparison, PC1-T series was depicted twice among the three groups. As shown in Fig. 3, the annual variations of the individual tree-ring indices series have similar patterns. There is no significant group difference among the three age classes. The series varied independently of their

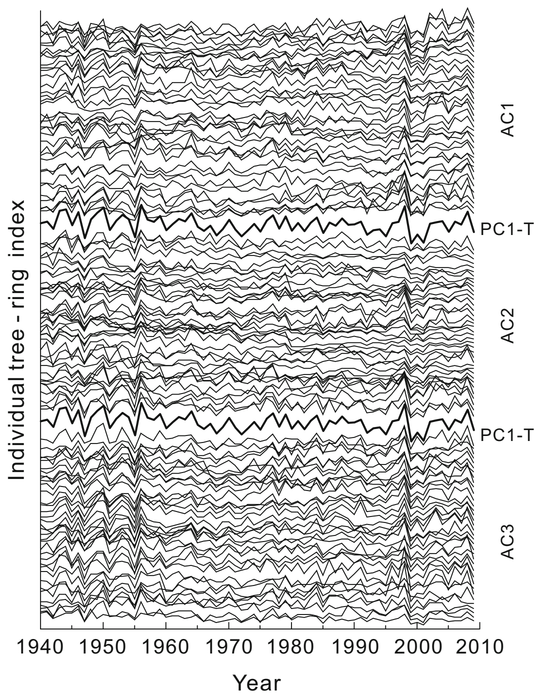

Fig. 3 Comparison of all the individual tree-ring indices (after being standardized) during their common period from 1940 to 2009. The *upper* (AC1), *middle* (AC2), and *bottom* part (AC3) represent the individual tree-ring indices of AC1, AC2, and AC3, respectively. PC1-T is the first principal component series of the total 108 tree-ring indices series in the sampling site

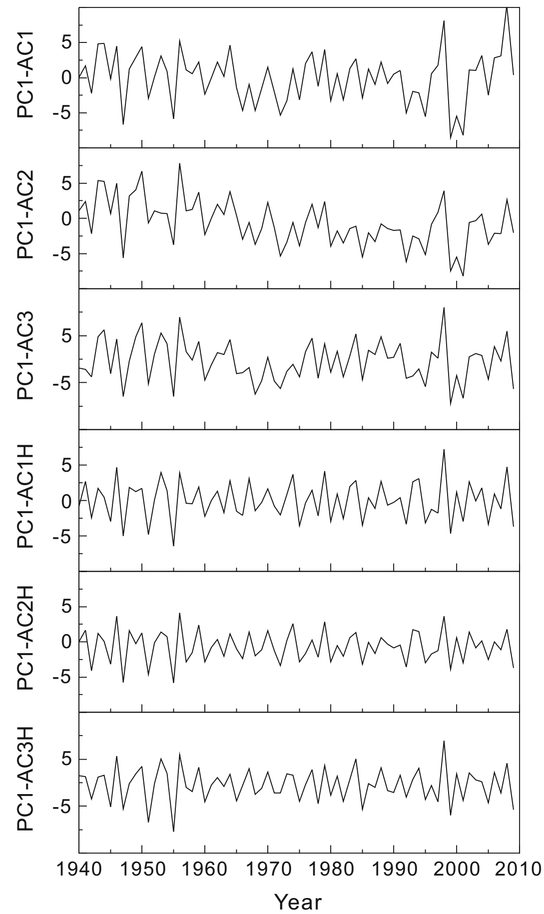

Fig. 4 Comparison of the first principal component series of the tree-ring indices (after being standardized) in the three individual age class from 1940 to 2009. PC1-AC1, PC1-AC2, and PC1-AC3 are the first principal component series of the individual tree-ring indices series in AC1, AC2, and AC3. PC1-AC1H, PC1-AC2H, and PC1-AC3H are the 5-year high-pass filtered series of PC1-AC1, PC1-AC2, and PC1-AC3

age class and showed generally consistent variation trends with the PC1-T series. Moreover, the first principal components of the tree-ring indices in every age classes were also extracted individually and were depicted as PC1-AC1, PC1-AC2, and PC1-AC3 in Fig. 4. Comparisons of the three first principal component series were to further examine whether there has group characteristics in some certain age class. To assess the frequency-dependent coherence, PC1-AC1, PC1-AC2, and PC1-AC3 were filtered by a 5-year high-pass filter (Fritts, 1976), which were depicted as PC1-AC1H, PC1-AC2H, and PC1-AC3H in the bottom half of Fig. 4. As shown, both of the original first principal component series and their high-pass components demonstrated high consistent variations, especially the latter one.

Climate-growth response of different age classes

Except for a number of chronology statistics that are slightly higher in the older trees than in the younger ones, the three age-class chronologies have similar variations. All of the age-class chronologies have similar signals and are highly consistent with the regional mixed-age TRW chronology.

Some studies have indicated that old trees have higher chronology statistics and a higher sensitivity to climatic variables than young trees. For example, the old *Pinus cembra* and *Larix decidua* in the Italian Alps have higher climate-growth responses than the young trees, and the tree-ring chronology statistics of *Larix decidua* are higher in the old trees (Carrer and Urbinati 2004). The tree-ring chronology statistics of *Picea abies* in the Alps are also higher in the old trees, and the radial growth of the old *Picea abies* trees has a highly significant response to May–June precipitation, whereas the young trees are insensitive to precipitation (Schuster and Oberhuber 2013). The growth in old *Quercus alba* trees of South Central Virginia, USA is more sensitive to drought than that of the young trees. Regarding the Chinese pine, Zhang et al. (2013a) found that the MS and SD of the old trees are higher than that of the young trees in the northeastern Tibetan Plateau,

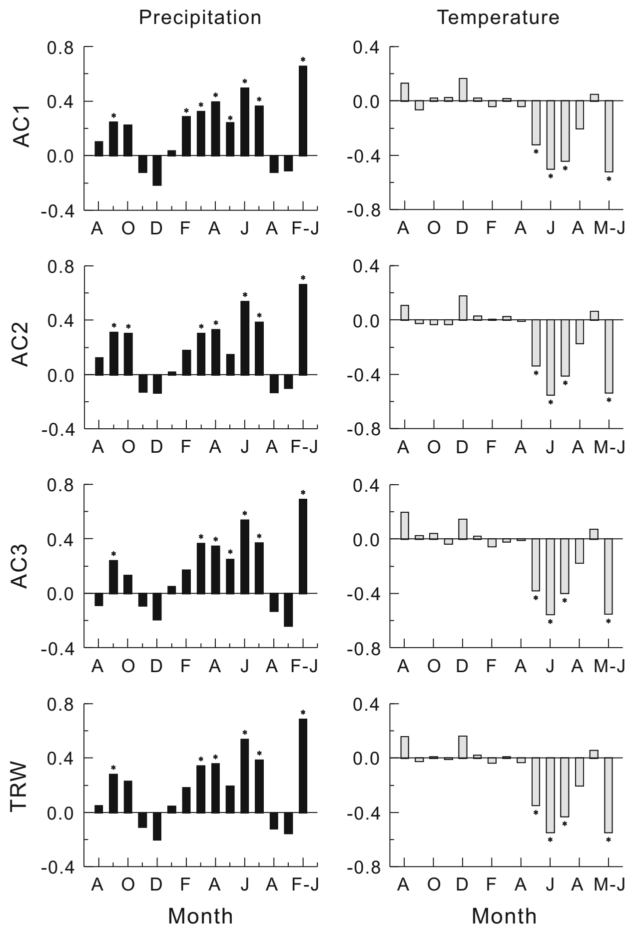

Fig. 5 Correlation coefficients between the tree-ring chronologies (AC1, AC2, AC3, and TRW) with the total monthly/seasonal precipitation (*left column*) and mean monthly/seasonal temperature (*right column*) from the previous August to the following September (1954–2009). F–J is from February to July. M–J is from May to July. The *asterisks* indicate 0.05 significance level

showing that the climate-growth responses are different between the young and old trees. The old Chinese pines have higher significant correlations with precipitation in May (positive) and with temperature in the previous October, previous December, and current September (positive) compared with that of young trees. However, the negative correlations between the radial growth of Chinese pines and temperature in the current January, June, and August are higher in the young trees than in the old trees (Zhang et al. 2013a). The increasing climatic sensitivity of old trees may be explained by an endogenous parameter linked to hydraulic conditions that becomes increasingly limiting as trees grow; thus, older trees have more hydraulic resistance and a higher climate sensitivity (Carrer and Urbinati 2004).

Correlation function analyses were employed to investigate the climate-growth relationships and to determine whether the old Chinese pines have higher climate-growth responses than young trees or the climate-growth response of Chinese pine in the study region is age independent. The individual correlation coefficients between the tree-ring chronologies (AC1, AC2, and AC3) with total monthly precipitation and mean monthly temperatures from the previous August to September in the following year were calculated. The correlations between TRW chronology and climatic data were also analyzed. All the correlation coefficients were depicted in Fig. 5.

The correlation analyses demonstrated that both precipitation and temperature affected the radial growth of Chinese pine in the study region, and similar climate-growth relationships with slight fluctuations occurred between the radial growth and climate. As shown in the left column of Fig. 5, all the significant correlation coefficients between the age-class chronologies and monthly precipitation have the same phase. Thus, the tree growth of different age classes has a nearly synchronous response to monthly precipitation.

Further, we can determine that almost all of the three age-class chronologies have significantly positive correlations with precipitation in the previous September and current growth season. In addition, the AC1 chronology is the only chronology that has a significant correlation with February precipitation, and the AC2 chronology is the only chronology that has a significant correlation with the previous October precipitation. The highest correlation coefficients are between the three age-class chronologies and June precipitation. Except for these slight differences, all of the other significant correlations between the individual age-class chronologies and monthly precipitation have similar or equal correlation coefficients.

The right column of Fig. 5 showed the relationships between age-class chronologies and temperature. The temperature from May to August mainly has negative effects on the radial growth of the Chinese pine in the study region; and the temperature of the previous August and December has positive effects on the tree growth. All of the correlation coefficients between the temperature from May to July and the three age-class chronologies are significant. The highest correlation coefficients between the age-class chronologies and temperature are also in June. Similar to precipitation, the differences in the correlations between the three age-class chronologies and monthly temperatures are also small and insignificant.

In dendrochronology, the responses of tree growth to seasonal or annual climate always have reasonable biological explanations. Seasonal or annual climate reconstructions are always more valuable in climate analyses and can supply comparable signals for other relevant research fields. Therefore, we analyzed the growth response of Chinese pine in different age classes to seasonal precipitation and temperature. Because the monthly precipitation from February to July and monthly temperature from May to July significantly affected the radial growth of the Chinese pine in the study region, we calculated the relationships between the age-class chronologies and the total precipitation from February to July and mean temperature from May to July. As shown in Fig. 5, the growth responses of the different age-class chronologies to seasonal precipitation and temperature also showed no significant difference.

Climate-growth response comparison between age-class chronologies and mixed-age chronology

In general, there is no significant difference in the response for the three age-class chronologies to different monthly and seasonal precipitation and temperature, which leads to the following questions: whether do the regional mixed-age TRW chronology has same responses to precipitation and temperature, and can a certain representative age-class chronology represent the population of Chinese pine in the study region? The bottom part of Fig. 5 described the responses of TRW chronology to monthly and seasonal precipitation and temperature. As shown, the regional mixed-age chronology has similar responses to monthly and seasonal precipitation and temperature as the three age-class chronologies. The correlation coefficients have no specific bias in the climate-growth responses of the three age-class chronologies. At times, the values are similar to the mean of the corresponding correlation coefficients between the climate and age-class chronologies or similar to the higher (lower) values. Certainly, these differences are slight and insignificant.

Conclusion

In this research, the characteristics and climate-growth responses of ring-width chronologies for the Chinese pine of North China were investigated. The results indicated that the climate-growth response of Chinese pine in North China is age independent. Although the MS, SD, mean correlations among all series, between trees, and within trees are slightly higher in the old group, the annual growth variations of the individual tree-ring index in sampling site are synchronous. There is no significant group difference among the three age classes. The individual tree-ring index series varied independently of their age class and showed generally consistent variation trends with the first principal component series of the total 108 tree-ring indices. The statistical indicators of the age-class chronologies have common features and all of the three age-class chronologies have similar growth pattern with the regional mixed-age chronology during their common period. The age-class chronologies and the mixed-age chronology have similar responses to monthly and seasonal precipitation and temperature.

The relationship analysis between climate-growth response and tree age in North China is in the preliminary stage. The study region and researched tree species are limited, and more extensive studies are required, including larger geographic scales and additional species, to determine whether tree age could influence dendroclimatic reconstructions in North China. Moreover, the original intention of this research was to determine whether the climate-growth response of Chinese pine is age related, which would produce a bias in the relevant climate reconstructions. Therefore, trees younger than 70 years old were not included in this research.

Author contribution statement Junyan Sun and Yu Liu conceived and designed the experiments. Yu Liu contributed analysis tools. Junyan Sun performed the experiments, analyzed the data, and wrote the manuscript.

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Conflict of interest We have no conflict of interest.

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