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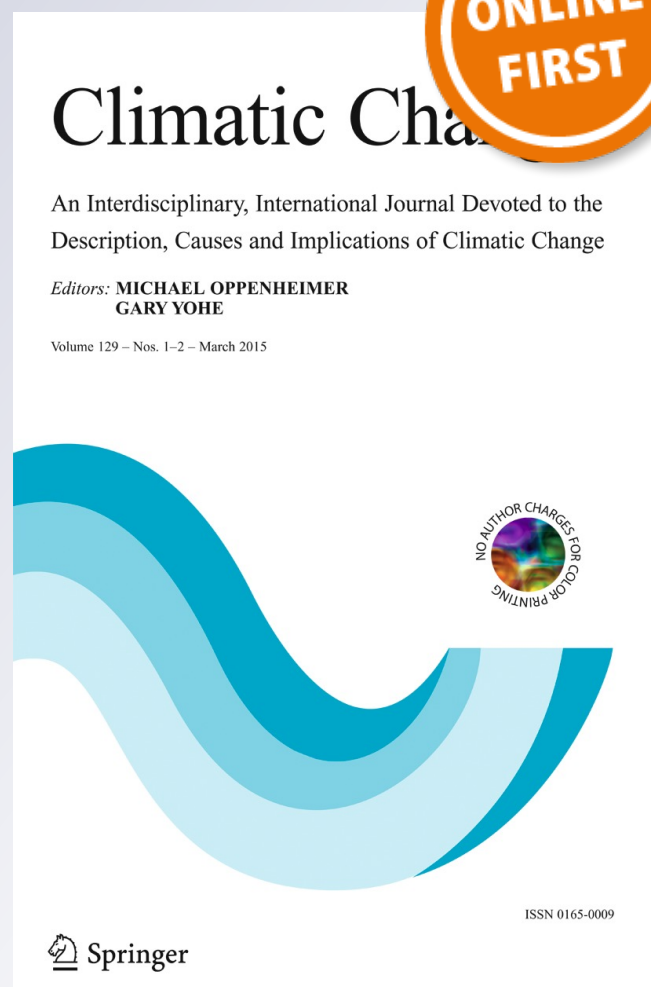
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Response of radial growth to warming and CO₂ enrichment in southern Northeast China: a case of *Pinus tabulaeformis*

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Abstract The southern part of northeast China has experienced a marked warming and drying climate. We provide dendrochronological evidence for atmospheric CO₂ fertilization and the impacts of warming on Chinese pine (*Pinus tabulaeformis*) growth. The results of this study show that increased temperature has a negative effect on pine growth during a major part of the growing season and a weakly positive effects on growth during the remaining portion of the year. The monthly temperatures explain ca. 20 % of the total variance in the annual radial growth of Chinese pine from 1901 to 2009. An increase of approximately 3–5 °C is the maximum that Chinese pine can tolerate in this region with an annual rainfall of 500–700 mm. Our results suggest a that there is a proportional response to warming only up to a maximum of 1 °C warming, and indicate the complexities of succession in forest ecosystems in terms of adaptation and evolution in local pine populations under a rapid warming condition. In addition, increasing atmospheric CO₂ concentrations have a positive effect on tree growth. This effect can be detected with conventional dendrochronological methods.

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1 Introduction

Temperature drives the energy and water budgets of ecosystems and is one of the key climate-related controlling factors of the distributions of tree species, the structure, distribution, and function of regional forest ecosystems (Bunn et al. 2005; van Mantgem et al. 2009). How temperature influences tree growth, positively or negatively, depends on the characteristics of the species and the conditions of the environment where the tree grows (Jacoby and D'Arrigo 1997; Piao et al. 2008). Trees from high latitudes and high-altitude typically show a positive response of radial growth to warmer temperatures (Esper et al. 2002). However, high-latitude warming can also lead to drought stress in some trees, a phenomenon referred to as “divergence” (Zimov et al. 1999; Barber et al. 2000). In some cases, warming can lead to increases in the death rates of trees and cause a regional decreases in forest biomass (van Mantgem et al. 2009).

Rapidly increasing CO₂ concentration in the atmosphere greatly contributes to global increases in surface temperature as greenhouse gas, and benefits plants significantly through its fertilization effect as the basic material of photosynthesis (IPCC 2014). The double-sided effect of CO₂ enrichment on trees can lead to a complexity and diversity of future forests because of the specific responses of particular species to increasing concentration of atmospheric CO₂ and the associated warming (Ahn and Brook 2008; IPCC 2014).

Rapid warming in China has had widespread impacts on endemic tree species such as Chinese pine, that are sensitive and vulnerable to environmental variation (Xu 1990; Liang et al. 2008). Tree species inhabiting the range limits areas of semi-arid and semi-humid regions are particularly impacted their ecophysiological property and habitability by rapid warming (Leng et al. 2008; Liang et al. 2008). Given the potential for effects of warming on trees, warming poses a potential threat to the stability of forest ecosystems in China. Accordingly, the objectives of the present study were (1) to detect the climate response of native trees (e.g. Chinese pine) at the northeastern most border of its distribution located in the southern part of northeast China and (2) to determine if CO₂ fertilization is detectable.

2 Materials and methods

2.1 Chinese pine and study area

Chinese pine is the dominant conifer in northern China and it is found in approximately 12 provinces (31°–44° N, 101°30'–124°45'E) (Xu 1990) in China. At the center of the distribution of Chinese pine, the annual mean temperature is 5–7 °C, the annual precipitation is 500–600 mm (Xu 1990). The sample sites included in this study are Yiwulvshan Mountain (Lvshan) at the western boundary of the Liaohe River plain, and Qianshan Mountain (Qianshan) at the eastern boundary of the plain (Fig. 1). This area and its vicinity represents a transition between the semi-arid and semi-humid climate zones occurring across southern northeast China which is controlled by continental monsoon climate regimes (Xiong et al. 2011). The region is also a transitional area between the North China Floristic Division and the Mongolian Steppe Floristic Division (Wu and Wu 1998). From 1901 to 2009, the annual mean temperature of the study area was 8.2 °C, and the annual precipitation was 620 mm (CRU TS3.1 0.5×0.5° grid point 41°N–42°N, 121.5°E–123.5°E). During this period, the mean temperature in January, the coldest month of the year, was –10.8 °C, whereas the mean temperature in July, the warmest month of the year, was 24.7 °C.

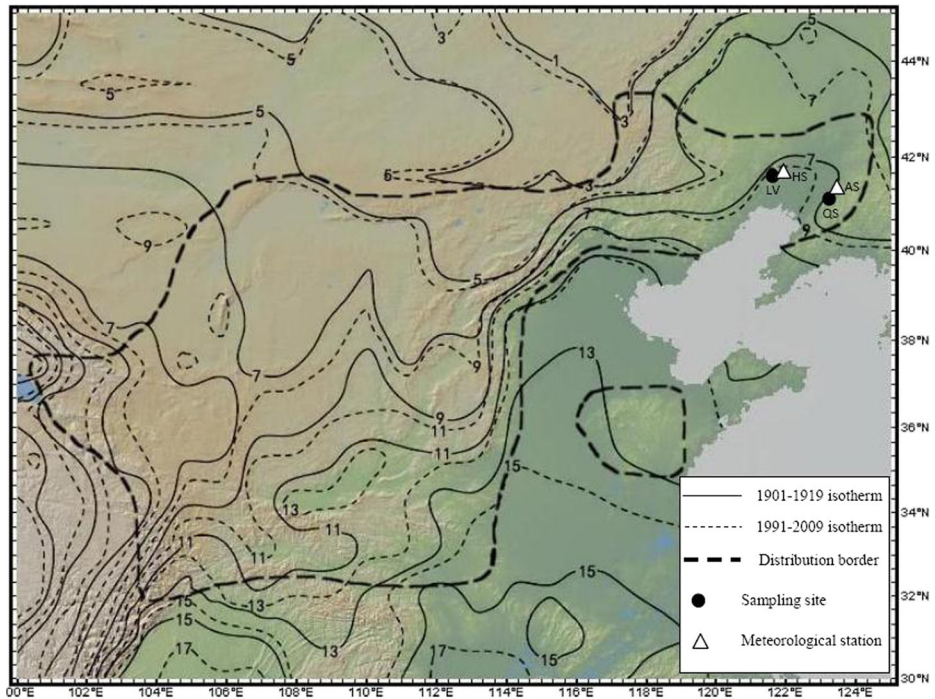


Fig. 1 Sampling sites at Yiwulvshan Mountain (LV, ca. 415 m, a.s.l) and Qianshan Mountain (QS, ca. 285 m, a.s.l), locations of meteorological stations for Heishan (HS) and Anshan (AS); the 1901–1919 isotherms ($^{\circ}\text{C}$, *thin solid curve*) and 1991–2009 isotherms ($^{\circ}\text{C}$, *thin dashed curve*) from CRU TS3.1 $1^{\circ}\times 1^{\circ}$ grid point; the area enclosed by the *thick dashed curve* is the approximate area of distribution of Chinese pine (Xu 1990)

2.2 Dendrochronological analysis for tree growth

A total of 233 cores (1–3 per tree) were taken from 126 Chinese pines in stands with low levels of human disturbance at the Lvshan (97 cores/56 trees) and Qianshan (136 cores/70 trees) sample sites. Conventional dendrochronological techniques (Stokes and Smiley 1968; Fritts 1976; Holmes 1983; Cook 1985) were used to develop the ring-width chronologies. Ring width was measured with a LINTAB5 measuring system with a resolution of 0.001 mm. Dating and measurement errors were further checked with COFECHA software (Holmes 1983). To preserve as much of the low-frequency signal as possible, we detrended most of the raw tree-ring measurements with straight lines or negative exponential curves (Cook and Holmes 1986). Tree-ring series with significant non-climatic disturbances that could not be fitted well with conservative curves were detrended with a rigid cubic spline curve with a 50 % cutoff equal to 2/3 of the length of each series. Based on a 30-year window with 15-year overlaps, the inter-series correlation ($r\text{Bar}$, the average correlation between series) and expressed population signal (EPS, the chronology signal expressed as a fraction of the total chronology variance), with an EPS threshold value of 0.85 or more, were employed to evaluate the time-varying signal strength over the length and the statistically reliable period of the chronology (Wigley et al. 1984). The tree-ring indices were averaged to generate a Standard chronology (STD) and a Residual chronology (RES) for each region using the ARSTAN program (Cook and Holmes 1986). The two kinds of chronologies were used to analyze low

and high frequency climate signal strength in tree rings. This analysis produced a 297-year chronology for Qianshan (1714–2010) and a 241-year chronology for Lvshan (1797–2010).

The running EPS of the standard chronology for Qianshan and Lvshan range from 0.760 to 0.998 and from 0.859 to 0.980, respectively, and the running r_{Bar} range from 0.175 to 0.405 and from 0.157 to 0.436, respectively, for 30-year intervals with 15-year overlaps. Based on the $\text{EPS} > 0.85$ criterion (Wigley et al. 1984) we truncated the Qianshan chronologies to 1776–2010 and 1828–2010 for the Lvshan chronologies, the chronologies of two region show adequate signal strength during their common period of 1828–2010 (Fig. 2; Table 1). The significant correlation between the STD/RES for Qianshan and STD/RES for Lvshan ($r_{\text{STD}} = 0.297$, $r_{\text{RES}} = 0.210$, $p < 0.05$) and the high percentage of variation explained by the first principal component of above STDs (PC1, 63.53 %) and the RES' (PC1, 59.86 %) during the common period (1828–2010) can be found. The values of the intercorrelation of the series

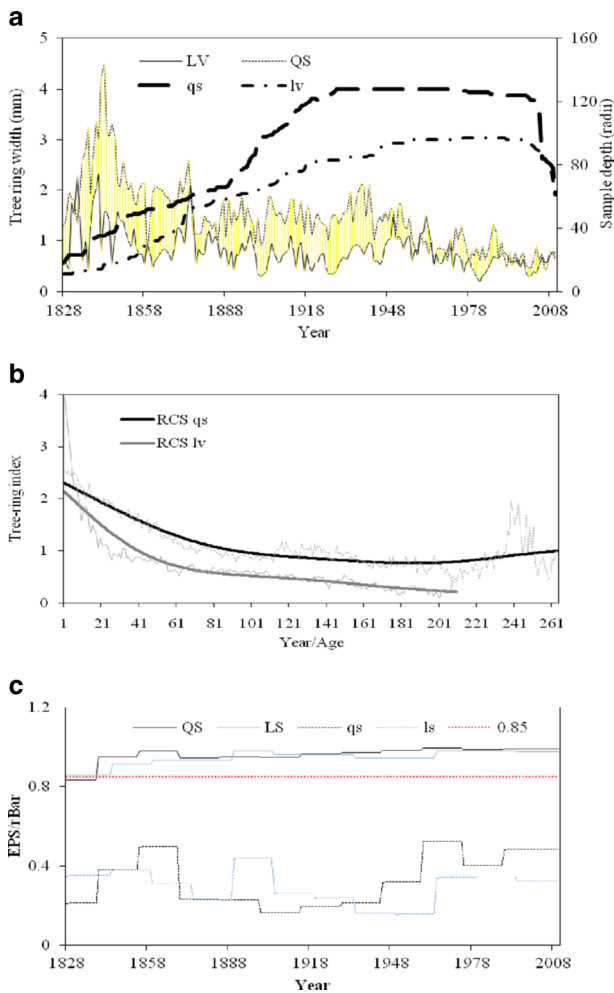


Fig. 2 Comparison of the raw tree-ring width chronology and the sample depth between Qianshan (QS/qs) and Lvshan (LV/lv) (a); age-related variation of tree-ring growth (b); and the expressed population signals (EPS) of the two standard chronologies during the period subsequent to 1828 (c)

Table 1 The statistics of the standard/residual chronology (STD/RES) for Qianshan and Lvshan

Parameters/chronology	Lvshan STD/RES	Qianshan STD/RES
Mean sensitivity	0.242/0.292	0.230/0.286
Standard deviation	0.362/0.272	0.318/0.237
Skewness	1.002/0.464	1.494/0.091
Kurtosis	4.608/3.988	10.938/4.718
1st-order autocorrelation	0.636/0.051	0.484/-0.079
Rbar	0.248/0.249	0.285/0.390
EPS	0.9573/0.963 (1828)	0.972/0.980 (1776)

EPS and Rbar indicate the mean expressed population signal and mean interseries correlation, respectively; the value for EPS within parenthesis indicates the year of EPS start to above 0.85

(0.444), the mean sensitivity (0.338) and the mean length of the series (132.9 years) for all raw measurements are all acceptable if we group assess all the samples from Qianshan and Lvshan together by COFECHA software. All above information indicate the high homogeneity of the forest stands and the regional environments. Therefore, the arithmetic average of the chronologies can be used to represent the regional profile of the radial growth of Chinese pine in 1828–2010. Our analysis is based on the arithmetic average of the two STDs or RESs. Several descriptive statistics commonly used in dendrochronology were also calculated (Table 1). In addition, the regional curve method (RCS, regional curve standardization) (Briffa et al. 1992) was used to detected the natural growth trend and ageing effect of the pines from different sites.

2.3 Meteorological data

Local meteorological data were obtained from the China Meteorological Data Sharing Service System (<http://cdc.cma.gov.cn/>). The regional climate data from CRU (Climate Reach Unit, UK) TS 3.1 were downloaded from the KNMI Climate Explorer (www.knmi.nl). The closest meteorological station to the Lvshan study site is the Heishan meteorological station (HS, 41°41' N, 122°05' E, 37.5 m a.s.l., 1956–2010), and the closest meteorological station to the Qianshan sampling site is the Anshan meteorological station (AS, 42°05' N, 123°00' E, 77.3 m a.s.l., 1951–2010). These stations were selected as sources of local meteorological data (Fig. S1).

The CO₂ data were obtained from the website of the National Oceanic and Atmospheric Administration (NOAA) (ftp://ftp.cmdl.noaa.gov/ccg/co2/trends/co2_annmean_mlo.txt). Before using the NOAA data, the CO₂ records from Waliguan, China (36°17' N, 100°54' E, 381 m a.s.l., 1994–2012) and Ulaan Uul, Mongolia (44°27' N, 111°5' E, 914 m a.s.l., 1992–2012) (<http://gaw.kishou.go.jp/wdcgg/wdcgg.html>), were used to test suitability for this study.

Two main methods were used to test for CO₂ fertilization on tree's radial growth. First, nonlinear regression methods were used to remove the low frequency increasing signal of CO₂ concentration since the comparison tree-ring chronology, is a standardized index, which was considered to not have much low frequency growth signal (Cook 1985). We then used the residual of CO₂ concentration time series as a parameter of high frequency CO₂ concentration variation (hereafter CO₂ Residual) to compare with tree-ring index for CO₂ fertilization testing. We also calculated the first order difference of the raw tree-ring chronologies and CO₂ concentration time series during the common period in order to test for CO₂ fertilization effect on tree growth at high frequency level. Second, multiple linear regression was used to quantify

the relationship between annual growth index and the precipitation and temperature from the nearest meteorological station or the CRU grid point (Table 2). The climatically induced variability was then linearly removed from the tree-ring chronology, and the residuals (hereafter, Nu-climate Residual) were tested for an increasing trend in growth over time that cannot be attributed to climate by using Sen's method (Sen 1968; Gedalof and Berg 2010), which is a nonparametric trend estimator (Sen 1968), premised on the assumption that the residuals should exhibit an increasingly positive bias over time due to CO₂ growth stimulations when the climate related variability have been removed from the chronologies (Gedalof and Berg 2010).

3 Results

3.1 Regional climate warming and (warming-induced) drying

Our study region has experienced a climate shift with clear warming and drying trends since the 1900s. During the past century, regional annual precipitation (1901–2009, CRU TS3.1 0.5×0.5° grid point data) averaged 620 mm and remained fairly stable (e.g., the longest significant periodicity of regional annual precipitation is the 5.2-year cycle in the period of 1901–2009; the first-order autocorrelation, 0.089, is near 0, indicating a time series with a typical “white noise” signal). Since 1949, precipitation has decreased significantly at a rate of -2.14 mm/year ($p < 0.05$). Figure 1 shows that the isotherms in the northern part of the region changed markedly during the past century, for example the latitude of the 7 °C isotherm shifted northward by 0.3–3.3° (ca. 30–300 km) in northeast China. On average, annual temperature has increased 1.53 °C since 1901. Annual and growing season temperatures (April–October (Song et al. 2010)) from 1901 to 2009, have increased significantly ($p < 0.01$) by 0.014 and 0.01 °C/year, respectively. These increases are higher than most other localities worldwide (IPCC 2014). Temperature-induced potential evapotranspiration (Thornthwaite 1948) have also increased significantly by 0.275 and 0.335 mm/year during the growing season and the entire year, respectively. The regional wetness index, defined as precipitation (P)/potential evapotranspiration (PE), decreased during the past century.

Table 2 Local (1956–2010) and regional (1901–2009) climate significance of the actual growth of Chinese pine

	Qianshan STD (RES) (Anshan: 1956–2010)/(regional: 1901–2009)	Lvshan STD (RES) (Heishan: 1956–2010)/(regional: 1901–2009)	Regional average STD (RES) (regional: 1901–2009)
T (%)	40.7* (31.6)/20.9* (15.9)	29.5 (31.7)/14.9 (13.0)	19.7* (18.1).
P (%)	46.9** (40.2*)/28.7** (31.7)	37.0* (46.6**)/25.0** (32.0**)	31.0** (37.6**)
P+T (%)	69.8** (60.2*)/36.3 (36.7)	59.2** (64.5*)/39.1** (42.8**)	43.0** (46.0**)
Precipitation (mm)	705 ↑	548 ↓	621 ↑
Temperature (°C)	9.5 ↑ **	8.3 ↑ **	8.2 ↑ **

↑ and ↓ denote increasing and decreasing linear trends, respectively, in local (Anshan and Heishan) meteorological variables during 1956–2010 and in regional (41°N–42°N, 121.5°E–123.5°E) CRU TS3.1 0.5×0.5° grid point temperatures during 1901–2009; * and ** denote the 95 % significance levels and the 99 % significance levels, respectively; T, P and P+T denote November–October temperature, precipitation, and temperature-plus-precipitation explanations, respectively, of the total variance of the actual radial growth of the pine; Precipitation and Temperature denote annual (November–October) variables

3.2 Growth-climate relationship and climate sensitivity assessment

A correlation analysis and a multiple linear regression analysis were performed on the climate-growth responses from the previous November to the current October. The climate-growth responses are very similar for the tree-ring data from the two regions (Fig. 3; S2) and are consistent when testing meteorological records rather than gridded data (Fig. S2).

Generally, precipitation data were positively correlated with the tree-ring data, especially during the growing season (April–October). At a regional scale, negative correlations between precipitation and tree rings were found in the coldest winter months (e.g., January–February) during last 100 years (1901–2009) (Fig. S2.b).

The temperature from February to July was negatively correlated with tree growth, particularly in May and June ($p < 0.05$). Temperature prior to the growing season and later in the growing season (November to January and August to October, respectively) generally showed a weakly positive correlation with tree growth, especially in Lvshan, a relative cold site. Similar correlations were not found in November and August in relative warm Qianshan site (Fig. 3). Winter temperature showed a negative correlation with radial growth at longer time scales (1901–2009), however the impact of temperature was very weak ($r = -0.017$). There was a significant correlation with temperature during the spring (March–June) ($p_{1901-2009} < 0.05$).

Chinese pines from Lvshan, a relatively cold and dry site, were more sensitive to the combined effect of regional moisture and heat than the pines from Qianshan, a relatively warm and wet site. Moreover, the explained variance was higher at Lvshan than at Qianshan (Fig 3; Table 2). The tree-ring width in the warm and wet site, Qianshan, was greater (mean tree-ring width 1.88 mm) than the dry site Lvshan (0.819 mm). A decreasing trend in the radial growth of the pines according to the standardized chronologies was found at all sampling sites during

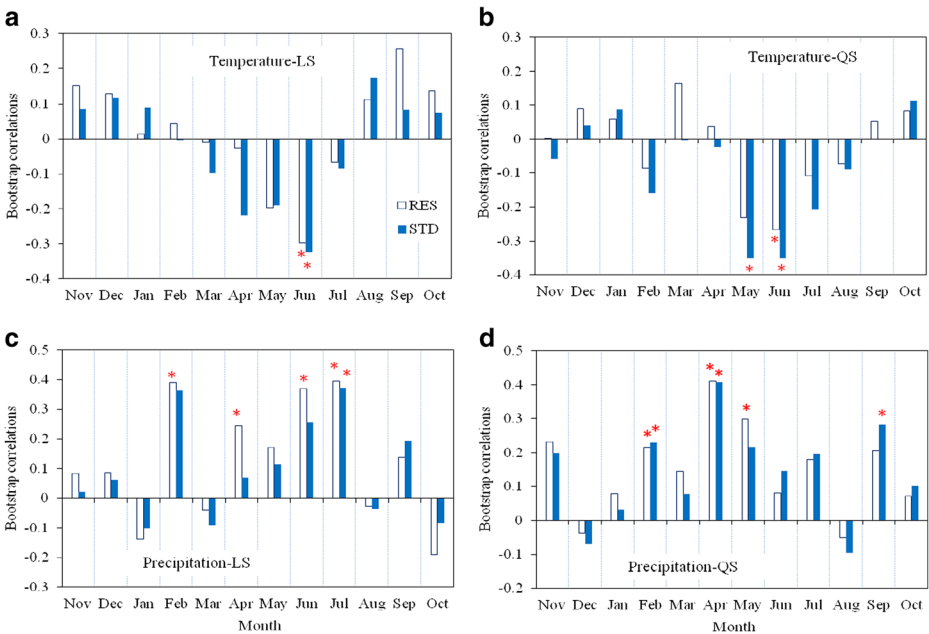


Fig. 3 Bootstrap correlations of the Standard chronology (STD) and Residual (RES) with precipitation and temperature for Lvshan (1956–2010; LS) Qianshan (1951–2010; QS). The asterisk, “*” indicates significant at 95 % confidence level

the past century. This decrease was significant beginning in the 1950s ($p < 0.05$), particularly in Lvshan ($p < 0.01$). The results of the multiple regression based on rainfall and temperature show that the regional radial growth of Chinese pine decreased ca. 1.5 % for every ca.1.5 °C increase in the annual mean temperature from 1901 to 2009.

3.3 Testing for the limited direct CO₂ fertilization of radial growth

The NOAA CO₂ data from the Mauna Loa Observatory in Hawaii can be used in this study because of its high consistence with the nearby CO₂ data during the common period, for example, the Waliguan records in China ($r_{1995-2012} = 0.997, p < 0.01$) and the Ulaan Uul records in Mongolia ($r_{1992-2012} = 0.999, p < 0.01$).

High positive correlations between the first order difference for CO₂ concentration and raw tree-ring width chronologies were found (Fig. 4b). After removing the linear trend of the first order difference of CO₂ concentration, the high frequency from CO₂ concentration and tree-ring data become more clear, e.g., the correlation coefficient with regional averaged tree-ring data changed from 0.252 to 0.314 ($p < 0.05$) (Fig. 4c). Also, the significant correlations ($p < 0.05$) between the CO₂ Residual (CO₂ data in which low frequency increasing trend were removed nonlinearly) and the STDs or RESs can be found (Fig. 4d).

No significantly increasing trend was found from the Nu-climate Residuals (tree-ring data in which climate inducing growth were removed) of tree-ring STDs/RES' during the period of

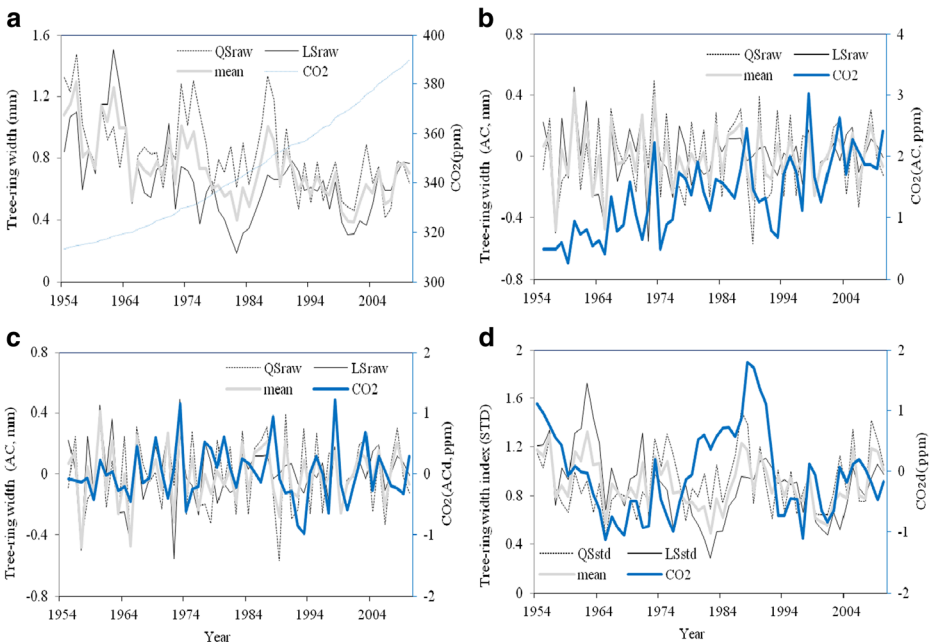


Fig. 4 Comparison of the tree-ring index and CO₂ concentration variables during the common period. The plot respectively is for raw tree-ring chronologies and original records of CO₂ concentration (a); the first order difference variables of raw tree-ring chronologies and original records of CO₂ concentration and the linear trend ($R^2 = 0.535$) removed first order difference variables of original records of CO₂ concentration and the first order difference variables of raw tree-ring chronologies (c); and low frequency increase trend (quadratic function, $R^2 = 0.999$) removed CO₂ data and tree-ring STDs (d). QSraw, LSraw, QSstd, LSstd and mean respectively is raw chronology for Qianshan, raw chronology for Lvshan, STD for Qianshan, STD for Lvshan, and the mean variables of above data in the corresponding plot

1954–2010 using Sen's method (Sen 1968). The Nu-climate Residuals of tree-ring data and the CO₂ Residual, high frequency variables of CO₂ concentration, show some consistency with each other during the common period (Fig. 5).

4 Discussion

4.1 Growth response to warming

Temperature is known to be negatively correlated with the radial growth of Chinese pine in most parts of northern China, including northeastern China (He et al. 2007; Chen et al. 2008; Liang et al. 2008). Similarly, our results indicate that temperature generally has a negative effect on the growth of Chinese pine, particularly during the growing season in southern northeast China. High temperatures can cause increases in transpiration, evaporation, moisture loss and the internal nutrient consumption of the trees, and temperature-related moisture stress could be further aggravated by increasing temperatures. For example, the temperature-induced potential evapotranspiration was 27.5 mm/°C during the growing season and 23.9 mm/°C over the entire year in the study area during the previous century. The water deficit induced by warming would produce narrow rings, whereas low temperatures during these seasons would promote the growth of Chinese pine.

Spring temperatures positively affect Chinese pine bud germination, the length of the growing season, photosynthetic vigor and the time span needed for photosynthetic recovery from winter to spring (Chen et al. 2008). Autumn temperatures, like spring temperatures, are related to the time span of the growth period and the growth increment in the current year. The winter has harsher effects on the survival of Chinese pine in our study area and vicinity than in other warmer locations because of the pine's specific northernmost location in its geographical distribution (Xu 1990; Liang et al. 2008) (Fig. 1). High winter temperatures could reduce the occurrence of injury to tree cells caused by freezing and could protect the shallow roots of trees because tree roots have a limited tolerance to subfreezing temperatures (Kozłowski 1971). Higher winter temperatures could also produce shallow frozen soils and higher ground temperatures. As a result, the relatively short time required for the ground temperature to recover and the relatively early period during which the growth of the root system occurred would extend the annual growth period of the trees. These factors are most likely responsible for the increased width of the tree rings.

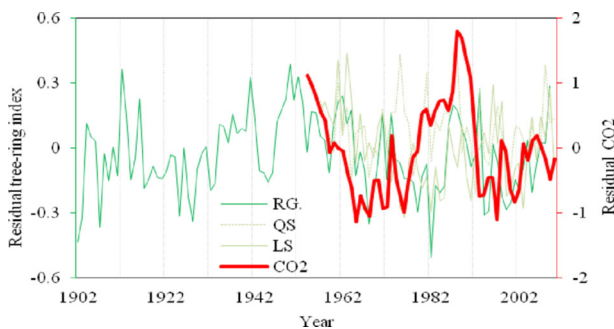


Fig. 5 Comparison of the tree-ring index and high-frequency variation of CO₂ (refer to Fig. 4d). The tree-ring index indicates the standard chronologies with the precipitation- and temperature-related variance removed. The statistics of the November–October precipitation and temperature-based multiple regression for tree-ring growth are shown in Table 2. RG, QS, and LS are the regional, Qianshan and Lvshan tree-ring indexes, respectively

As a key factor protecting plants during the winter in the study area, snow cover may provide a relatively warm underground environment for tree growth. Heavier snow protects plants more effectively than thinner snow cover from wind and the extremes of winter temperature and reduces temperature injury to the roots under extreme or long-term cold conditions. Moreover, winter precipitation in the form of snow enhances the storage of soil moisture, reduces the impacts of heavy water loss through evaporation and benefits growth during the subsequent growing season.

Although beneficial effects of temperature on growth could be found at specific times, e.g., prior to the growing season and later in the growing season (November to January and August to October, respectively), negative effects of temperature represent the strongest influence of climate on the growth of Chinese pine in the study area and its vicinity.

4.2 Northward shifts in species distributions caused by warming

Climate warming causes northward shifts in the distributions of tree species. Moreover, it fragments the current geographical distribution of the tree species (Xu 1990; He et al. 2005; Leng et al. 2008). The small patches that result from habitat fragmentation have potential as habitats for tree species because the patches show the diversity and complexity typical of multiple environments (He et al. 2005; Leng et al. 2008). Increases in winter temperature will produce a relatively warm and temperate environment. These conditions will reduce the hardiness level (ca.1–2 °C) of the Chinese pine in new regions to the north where the pine is transplanted (here, hardiness is a plant's tolerance to cold temperatures). Temperature increases will also allow the pine to grow in the northern areas of its distribution. These effects will be particularly marked during the growing season itself. Through these mechanisms, a warming climate could result in a more northern zone (newly colonized areas) of the distribution of Chinese pine. A local annual mean air temperature of 8.3–9.5 °C will increase to 11.3–14.5 °C as the result of a ca.5 °C increment over 80–100 years. The new mean temperature will be near the limits or out of the range of the annual mean temperature that defines the viability and distribution of Chinese pine (ca.3–ca.15 °C). This temperature range is shown by the isotherms for 1901–2009 (Fig. 1). The results of this study also suggest that Chinese pine cannot tolerate a temperature increment of ca.3–5 °C in a region such as the study area, which has an annual rainfall of 500–700 mm and shows a slight decrease in annual rainfall over time. The significant linear decrease in the growth of Chinese pine found by the dendroclimatological simulation (ca.–1 %/+1 °C) indicates some of the characteristics of the pine's response to climate warming. This result suggests the existence of a very narrow temperature limit (<1 °C) for the pine's proportional response to climate change and indicates the complexities of succession in forest ecosystems and the potential for adaptation and evolution in local populations of pines.

4.3 The potential effects of CO₂ enrichment

CO₂ enrichment has two different key effects on the terrestrial and ocean biospheres, warming and fertilization (IPCC 2014). The effects of warming on Chinese pine has been discussed above. The primary focus of the following discussion is on CO₂ fertilization and difficulties in isolating a fertilization signal.

The fertilizing effect of CO₂ appears to be more easily detected in a short-term experiment involving a doubling of the CO₂ concentration (Idso 1999) than in a stepwise increase in atmospheric CO₂ concentration. The effects of CO₂ enrichment, particularly the effect of a stepwise enrichment on the radial growth of the tree, are often removed by standard

dendrochronological detrending procedures (Cook 1985; Cook and Holmes 1986; Frank et al. 2009). Therefore, is very difficult to directly obtain acceptable evidence of CO₂ fertilization in tree-ring records. The controversy to detect and document CO₂ fertilization (Koutavas 2008; Frank et al. 2009) illustrates the pitfalls associated with the use of conventional dendrochronological methods to detect the effects of CO₂ fertilization. Our data shows that the conventional dendrochronological technique can capture some CO₂ induced tree growth influence (Figs. 4 and 5), although the current dendrochronological detrending method cannot individually differentiate the total signal associated with tree rings and completely remove this signal (Cook 1985; Cook and Holmes 1986; Frank et al. 2009). In addition, the detected signal of CO₂ concentration variability in tree growth can also be disturbed by climate extremes, for example, the correlations between the residual CO₂ data and the STDs or RES' could be improved once the period 1981–1984, the extremely low precipitation time in 1957–2010, was not considered (e.g., the annual precipitation deficit respectively is ca.41 % (228 mm), 29 % (163 mm), 36 % (202 mm) and 23 % (130 mm) from 1981 to 1984 as compared to the average (555 mm) of 1957–2010 in Lvshan): their correlation coefficients changed from 0.296 ($p < 0.05$) to 0.409 ($p < 0.01$). As a result, the effect of high-frequency fluctuations in CO₂ concentrations reflected by the tree rings could also be extracted after the principal climate (precipitation and temperature) signal was removed (Fig. 5). Climate extremes, like above mentioned precipitation deficits, could also disturb the detection of CO₂ concentration variability in tree growth based on the comparison of Nu-climate Residuals of tree-rings and CO₂ Residual: the correlation coefficients of them improved from 0.290 to 0.324 ($p < 0.05$) for the entire study region once the precipitation data of 1981–1984 were excluded (Fig. 5).

Trees have developed special physiological and morphological mechanisms for acclimating and adapting to changes in CO₂ concentrations, e.g., the reduction in stomatal conductance (Rey and Jarvis 1998), a gradual reduction in stomatal frequency (Wagner et al. 1996) and a decrease in photosynthesis (Saurer et al. 2003) under elevated CO₂ concentrations (the trees exhibit low photosynthetic affinity for CO₂ when grown under high (surplus) CO₂ conditions). These properties can change over hours or years when trees are grown under various CO₂ conditions. The decline in the enhancement of radial growth induced by elevated CO₂ (Tognetti et al. 2000; Adam et al. 2004) and the senescence in trees under long-term elevating CO₂ conditions (Warren et al. 2011; Way 2011) also indicate tree's acclimation to increases in CO₂, and suggest that the long-term fertilization effect of CO₂ is not distinguishable from age-related tree radial growth trend. Our data, based on the Sen's method (Sen 1968), supports the hypothesis that trees have a "CO₂ acclimation" response and that tree's radial growth may not totally exhibit an increasing trend under a direct CO₂ fertilization (Gedalof and Berg 2010).

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