Dendrochronologia 60 (2020) 125683

Contents lists available at ScienceDirect

Dendrochronologia

journal homepage: www.elsevier.com/locate/dendro

Climate signal shift under the influence of prevailing climate warming – Evidence from *Quercus liaotungensis* on Dongling Mountain, Beijing, China

Maierdang Keyimu, Jingshu Wei, Yuxin Zhang*, Shuang Zhang, Zongshan Li*, Keming Ma, Bojie Fu

State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China

ARTICLE INFO

Keywords:
Ring width
Cooling
Warming
Climate signal alteration
Tree growth decline

ABSTRACT

Increasing climate warming is inducing drought stress and resulting in forest growth decline in many places around the world. The recent climate of northern China has shown trends of both warming and drying. In this study, we obtained tree ring width chronology of *Quercus liaotungensis* Koidz. from Dongling Mountain, Beijing, China. We divided the temperature series of the study area into cooling (1940–1969) and warming intervals (1970–2016). The climate–tree growth response analysis showed that temperature exerted a limiting impact on the annual radial growth of *Q. liaotungensis* during the cooling period, whereas the influence of temperature was lower during the warming period. The moving correlation analysis showed that the influence of summer temperature decreased with the warming climate since the 1970s, and that the influence of winter and spring temperatures decreased since the 2000s. The correlation values between the chronology and precipitation decreased during the cooling period, whereas spring and early summer precipitation correlations began to increase in the 1970s and reached significance ($p < 0.05$) in the 1990s. Our results show that the positive influence of temperature on radial growth of *Q. liaotungensis* in the study area has weakened, whereas precipitation has become the dominant regulator with climate warming. These findings suggest that forest growth on Dongling Mountain will decline if climate warming continues in the future.

1. Introduction

Global climate change is projected to yield increases in frequency and intensity of droughts under warming temperatures (IPCC, 2013; Barber et al., 2000; Hoerling and Kumar, 2003). In recent decades, intense droughts have led to declines of tree growth and increasing mortality in many forest sites globally (Breshears et al., 2005; Allen et al., 2010; Williams et al., 2010, 2013). Relevant studies have reported that diminishing temperature constraints on forest growth and shifts from temperature limitation to water limitation have been the major drivers of declining forest growth rates (Barber et al., 2000; Williams et al., 2011; McDowell, 2011; Charney et al., 2016; Girardin et al., 2016; Babst et al., 2019), which implies the alteration of tree growth response to climate through heterogeneous climatic periods.

Northern China has already started to experience climatic warming and temperature-induced drought (Xu and Wei, 2006; Zhang et al., 2011; Liu et al., 2013a); these factors might decrease the growth and increase the mortality of temperate forests, as in many other places around the world (Adams et al., 2009; Martínez-Vilalta et al., 2012; Williams et al., 2013). Tree rings reflect different climate signals in cool/moist and warm/arid regions (Hughes et al., 1994; Yasue et al., 1997; Lindholm and Eronen, 2000; D'Arrigo et al., 2005; Liang et al., 2009; Fan et al., 2009; Li et al., 2015; Yang et al., 2014; Gou et al., 2015). It is also reasonable to hypothesize that the climate signals of tree rings in one geographical location might vary through different climatic periods. In the present study, we obtained ring width parameters of *Q. liaotungensis* on Dongling Mountain, Beijing, China, and analyzed the climate response relationships between the tree ring width chronology and climate variables. The main objectives of our investigation were to reveal the non-stationary characteristics of radial tree growth response and shift of climate signals based on tree ring widths under the prevailing climate warming. Our hypothesis is that during cooling periods, the ring widths of *Q. liaotungensis* reflect the temperature signal, whereas during warming periods, the climate signal shifts to water stress. Our findings may provide evidence not only to understand the reaction of *Q. liaotungensis* to ongoing regional climate change but also to further understand the alteration of tree ring responses under different climatic periods.

* Corresponding authors.
E-mail addresses: yxzhang@rcees.ac.cn (Y. Zhang), zsli_st@rcees.ac.cn (Z. Li).

https://doi.org/10.1016/j.dendro.2020.125683
Received 29 June 2019; Received in revised form 4 February 2020; Accepted 19 February 2020
Available online 25 February 2020
1125-7865/

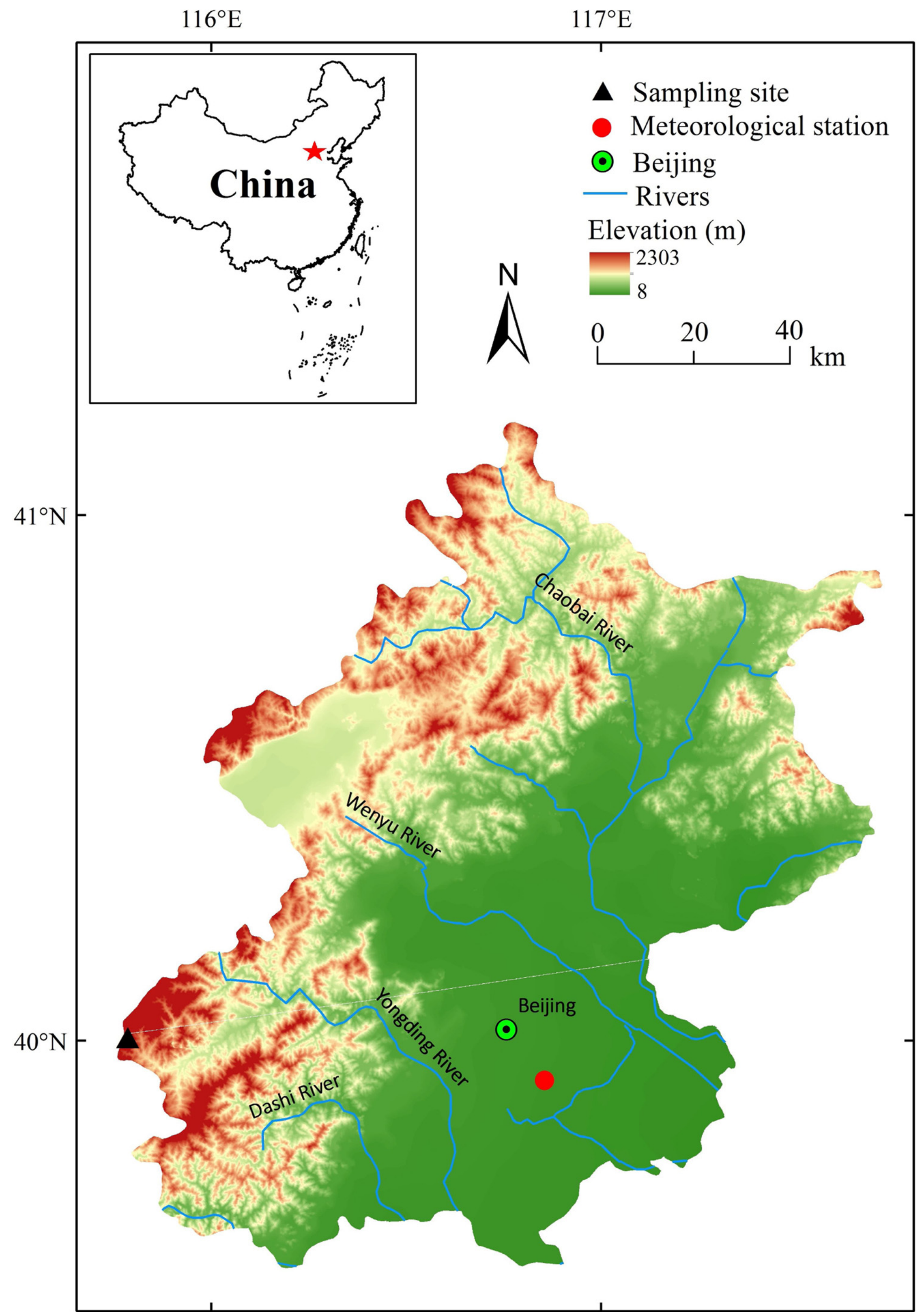

Fig. 1. Locations of the tree ring sampling site and the meteorological station in Beijing, China.

2. Materials and methods

2.1. Study area

The study area is located on Dongling Mountain (40.25 °N, 115.25 °E), Beijing, China, approximately 100 km west of the city (Fig. 1. The highest peak of Dongling Mountain is 2,303 m a.s.l. This area is characterized by a warm temperate semi-humid continental monsoon climate. The annual temperature is ranged from 5 to 10 °C from 1951 to 2008) (Feng et al., 2009), the average annual precipitation is 500–650 mm (1951–2017), and nearly 80 % of the precipitation occurs during the summer (June–August) (Ma et al., 2018). The mountain soil is of the brunisonic soil type, with approximate depth of 30 cm (Sun, 1997). The main landform is eroded mountain land, and the topography is relatively steep with a slope of 30–40°.

Most of the warm temperate deciduous broad-leaved forests in China have been lost because of human-induced disturbances. Dongling Mountain is an area relatively well preserved from vegetation exploitation (Ma et al., 1995a). The vegetation structure has a typical characteristics of the northern sub zone of the warm temperate deciduous broad-leaved forest region (Liu et al., 2011). Thus, Dongling Mountain has high research value to study a warm temperate forest community in northern China (Ma et al., 1995b; Wu et al., 2002; Zhang et al., 2009; Ma et al., 2018). *Quercus liaotungensis* Koidz. is a native tree species, and the most abundant tree species in the study area (Feng et al., 2009). It is also the oldest in comparison with other tree species

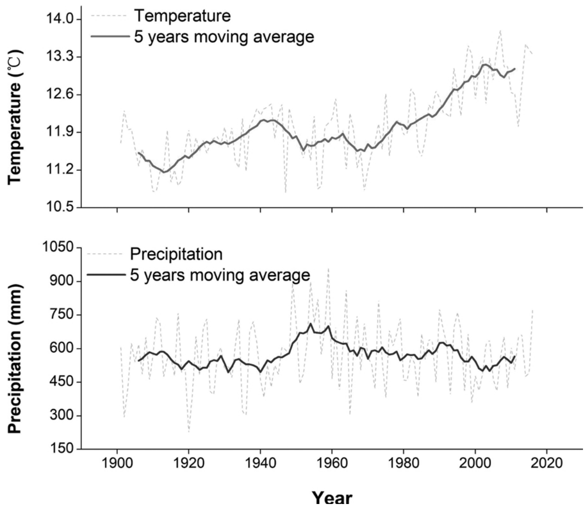

Fig. 2. Trends of climate variables include annual temperature and precipitation on Dongling Mountain, Beijing, China, based on CRU gridded data; time span: 1901–2016.

present in the area; therefore, it is an important dendrochronological resource to study the impact of climate change on forest growth in northern China. The other main arbor species are *Betula dahurica* Pall. and *Populus davidiana* Dode. The main shrub species are *Syringa pubescens* Turcz., *Abelia biflora* Turcz., *Corylus mandshurica* Maxim., *Deutzia parviflora* Bge., and *Rhododendron micranthum* Turz. (Liu et al., 2011).

2.2. Climate data

The length of the climate dataset from the China Meteorological Administration weather station in Beijing was only 66 yrs (1951–2016), which was too short to split into periods of temperature increase and decrease. Therefore, we used the gridded datasets of the Climate Research Unit (CRU) TS 3.22 (Zhang et al., 2019) to carry out tree growth–climate response analysis. Temperature and precipitation data were obtained using the KNMI Climate Explorer (data first access was on 12 November 2018, updated access was on 18 April 2019). Before using the CRU data, we developed correction equations (Fig. 3) based on the correlation between weather station data and CRU data (Cao et al., 2018), and then calculated temperature and precipitation before the 1950s. Finally, the corrected climatic data were used for the analysis of climate and tree growth relationships. According to the climate data, Dongling Mountain has experienced clear climate fluctuation from 1910 to 2016. We divided the temperature series into three time spans: warming (1910–1939), cooling (1940–1969), and warming (1970–2016) periods. We used Spearman rank correlation to confirm this variation of temperature (Table 1).

2.3. Tree ring data and chronology development

The tree ring samples of *Q. liaotungensis* were collected on Dongling Mountain at the elevation of 1,800 m a.s.l. upper treeline. Tree ring cores $n = 37$) were extracted from each tree along an axis perpendicular to the slope inclination to avoid the impact of tension wood, at approximate breast height (1.3 m) using 5-mm increment borers. In the laboratory, the samples were processed following standard dendrochronological techniques (Stokes and Smiley, 1996). Air-dried and mounted cores were sanded to a flat surface using successively finer sandpaper grits from 300 to 1,200, and were subsequently scanned using a TSD4800 flatbed scanner to generate digital images for dendrochronological analysis. The scanner was pre-calibrated for pixel size to measure the sizes of objects (ring widths). We used the WinDENDRO 2017a tree ring measurement system (Regent Instrument, 2020) to determine the ring widths from the scanned images. The data were subsequently converted to Tucson (decadal) format. The cross-dating was first checked visually, and quality was then controlled by the COFECHA program (Holmes, 1983). Following the standard order of dendrochronological study, we detrended the original chronology to remove ring width variation unrelated to climate (i.e., tree age-related growth traits) using a negative exponential model (Cook and Kairiukstis, 1990; Carrer and Urbinati, 2006; Fan et al., 2010). The dimensionless index of tree ring width after detrending was then averaged to achieve standard chronology using Tukey's biweight robust mean, which enhances the common signal and reduces the effect of outliers (Cook, 1985). Detrending and chronology development were carried out using the "dplR" package (Bunn, 2008; Bunn and Korpela, 2018) in R (R Core Team, 2019). The common statistics of mean sensitivity, standard deviation, inter-series correlation (*r*bar), first order auto-correlation (AC), expressed population signal (EPS), and signal-to-noise ratio (SNR) were used to evaluate the chronology. The length of the most reliable chronology was truncated at the EPS reaching a threshold value of 0.85 (Wigley et al., 1984).

2.4. Climate–tree growth relationship analysis

Correlation analysis function of the Dendroclim 2002 program was used to carry out tree growth–climate relationship analysis (Biondi and Waikul, 2004; Zang and Biondi, 2015). Static correlation between the chronology and monthly temperature was run in three different climatic periods (first warming, cooling, and second warming) using Pearson correlation coefficients (at the 95 % significance level). However, the correlation results during the first warming period was not as strong as the second warming period. Therefore, the static correlation focused on the cooling and second warming periods. The static correlation between chronology and monthly precipitation also focused the period from 1940 to 2016 in parallel to the chronology – temperature correlation. We also carried out moving correlation analysis between the ring width indices and monthly climate variables using the Dendroclim 2002 program at a 32-year moving interval. Aggregated temperature and precipitation of three, four, and five month seasons were investigated for moving correlation analysis as well. Considering the "legacy effect" of previous-year climatic conditions on the current year tree growth (Fritts, 1976), the climate–tree growth relationship analysis period included the months from June of the previous year (P) to October of the current year (C). Correlation results were adjusted with a Bonferroni multiple analysis correction (Cerrato et al., 2019).

3. Results

3.1. Statistical characteristics of tree ring width chronology

Fig. 4 depicts the tree ring width chronology of *Q. liaotungensis* on Dongling Mountain. The length of the reliable chronology (EPS > 0.85) extended from 1910 to 2016, and included a minimum of five tree ring samples. The inter-series correlation (*r*bar) of the chronology was 0.31, implying a higher common signal among the individual trees of the chronology. The mean sensitivity and standard deviation of the chronology were 0.30 and 0.57, respectively, indicating relatively strong inter-annual variations in the ring-width series. The first order autocorrelation was 0.55, which implies that the conditions that caused a ring to be narrow (or wide) in a given year carried over their effect on growth in the following year. The SNR was 12.00, which indicates that the radial growth of individual trees responded to common factors.

3.2. Climate–tree growth response analyses

The results of correlation analysis between chronology and monthly temperature were different during the heterogeneous climate periods. During the cooling period (1940–1969), the correlation between

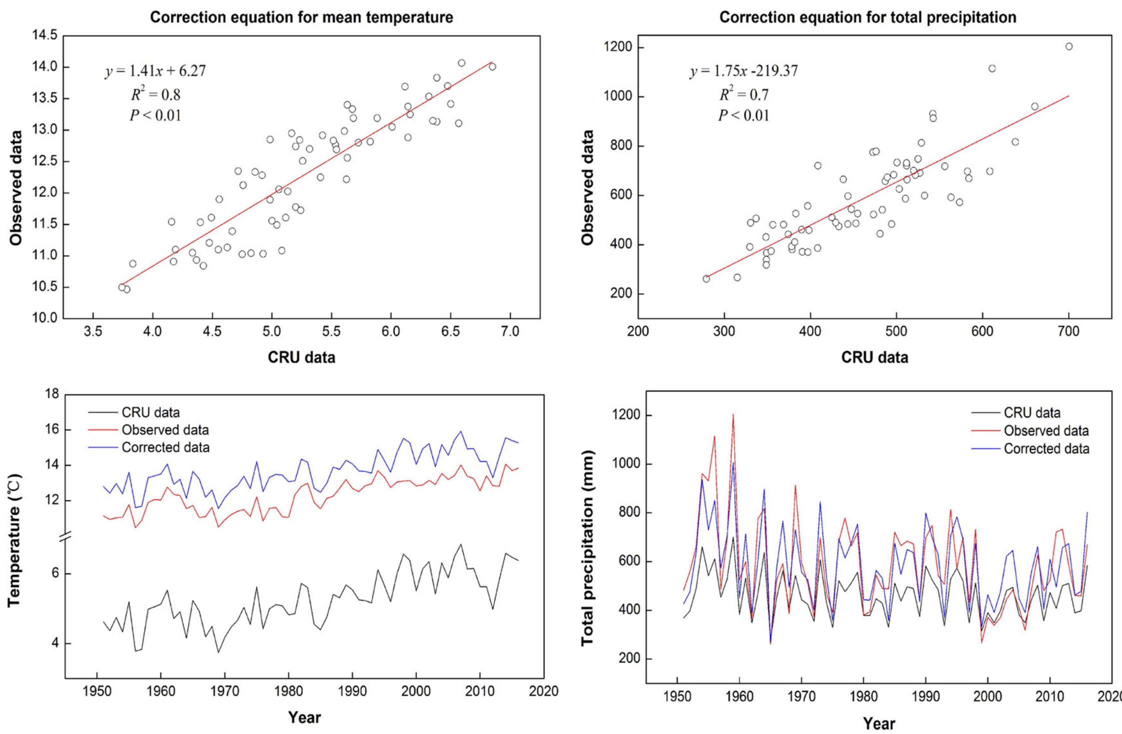

Fig. 3. Correction equations and corrected climatic data of annual mean temperature (*left*) and annual total precipitation (*right*).

Table 1
The mean of climate parameters, standard deviation, and Spearman rank correlations.

Climate data	Period	Temperature (°C)	Precipitation (mm)
CRU	1910–1939	0.65 ($p < 0.001$)	−0.04 ($p > 0.05$)
	Mean (SD)	4.52 (0.45)	436.84 (90.48)
	1940–1969	−0.42 ($p < 0.05$)	0.29 ($p > 0.05$)
	Mean (SD)	4.79 (0.55)	475.67 (107.15)
	1970–2016	0.75 ($p < 0.001$)	−0.03 ($p > 0.05$)
	Mean (SD)	5.52 (0.69)	448.3 (78.49)
Weather station	1970–2016	0.84 ($p < 0.001$)	−0.12 ($p > 0.05$)
	Mean (SD)	12.6 (0.87)	550.27 (141.21)

SD: standard deviation, *p*: significant level.

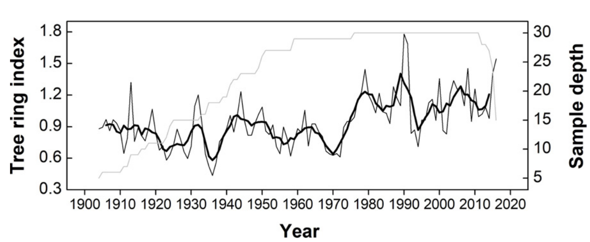

Fig. 4. Tree ring width chronology of *Q. liaotungensis* on Dongling Mountain, Beijing, China. The time span of reliable chronology is 1910–2016.

chronology and temperature was positive in P-June ($r = 0.39$, $p < 0.05$) and P-July ($r = 0.49$, $p < 0.01$), as well as in C-January ($r = 0.43$, $p < 0.05$) (Fig. 5a). Although this correlation reached significance only in three months, the correlation values were positive during most of the time windows except in P-November ($r = -0.01$, $p > 0.05$). In the warming period (1970–2016), the chronology was positively correlated with the monthly temperatures of P-December ($r = 0.36$, $p < 0.05$) and C-September ($r = 0.35$, $p < 0.05$) (Fig. 5b). In contrast to the cooling period, the correlation between chronology and temperature has weakened during the warming period (Fig. 6).

Seasonal correlation analysis between chronology and temperature (3, 4, and 5 months) in the two different climate periods showed that the correlation between temperature and chronology strengthened with aggregating temperature over 5 months during the cooling period (Fig. 7, *upper panel*). However, the effect of aggregating different months was not obvious during the warming period (Fig. 7, *lower panel*).

We also performed moving correlation analysis between chronology and monthly temperature (Fig. 8). Chronology showed increasing correlation values with P-June and P-July temperature during the cooling period of 1940–1969, with significance ($p < 0.05$) reached around the 1950s. Correlation with C-January also increased, but reached significance earlier in contrast to P-June and P-July, and remained relatively stable. In the warming period of 1970–2016, the correlations with P-June, P-July, and C-January decreased. After the 1980s, the correlations with P-June and P-July remained below the level of significance ($p > 0.05$), and the C-January correlation decreased from the 1990s onward. The general variation of correlation values in P-September, P-October, P-December, and C-February increased from the 1940s until the 2000s, and all of them started decreasing afterward.

The moving correlation analysis between the chronology and aggregated temperature (3–5 months) also showed unstable characteristics of temperature influence on tree growth during the different climatic periods (Fig. 9). The correlation values of chronology with temperature in all aggregation forms progressively increased during the cooling period. The correlation values with summer temperature decreased steadily after the 1970s, whereas the correlation values with winter, spring, and autumn temperatures continuously increased. The general trend of chronology–temperature correlations decreased after the 2000s.

The fluctuation features of precipitation in the study area were not as obvious as those of temperature. Therefore, we have not divided the precipitation series into different intervals. We carried out Pearson correlation analysis on the relation between the chronology and precipitation for the period 1940–2016 (Fig. 10). The results showed that the chronology was positively correlated with P-September ($r = 0.31$, $p < 0.01$), C-February ($r = 0.23$, $p < 0.05$), C-April ($r = 0.30$, $p < 0.01$), and C-May ($r = 0.36$, $p < 0.001$) precipitation values.

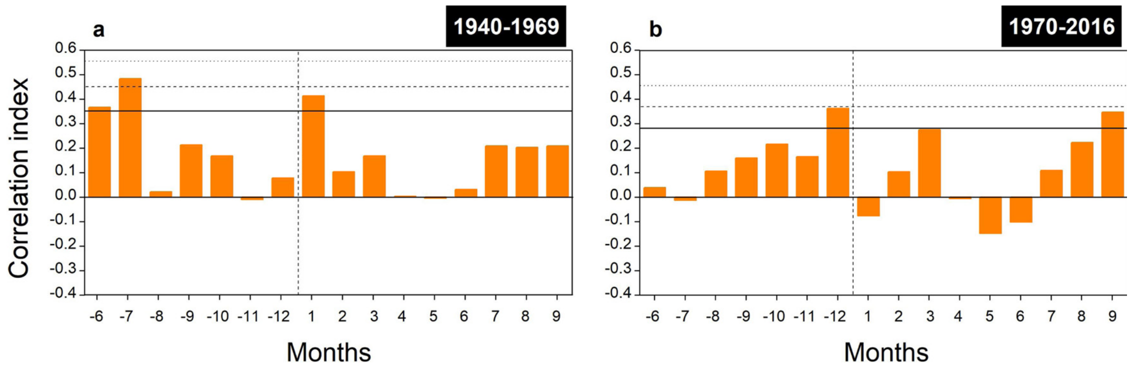

Fig. 5. Pearson correlation between chronology of *Q. liaotungensis* and temperature (a, b) for the different periods (1940–1969 and 1970–2016). The vertical dashed line represents the border of previous and current growing years. Horizontal solid, dashed, and dotted lines represent Bonferroni-corrected *p*-value levels of 0.05, 0.01, and 0.001, respectively. Numbers below the *x*-axis refer to the corresponding months from previous June (−6) to current September (9) in the correlation analysis.

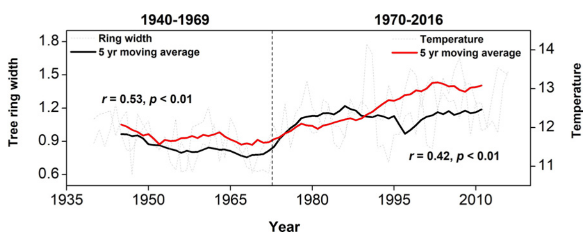

Fig. 6. Linear correlations between temperature and chronology of *Q. liaotunensis* in two different climatic periods.

The moving correlation analysis between chronology and monthly precipitation showed that the correlation values of chronology with C-April and C-May precipitations first decreased and then progressively increased after the 1970s (Fig. 11). The variation of P-September precipitation correlation showed a fluctuation pattern, but increased after the 1990s. The correlation values between chronology and precipitation of C-February, and C-March also increased with climatic warming and reached significance ($p < 0.05$) around the 1980s–1990s.

Correlation between chronology and precipitation of aggregated months demonstrated that the chronology had higher correlation with precipitation of spring and early summer (Fig. 12). The consistent higher correlation values were appeared in April, May, and June.

The results of moving correlation analysis between chronology and aggregated precipitation of 3–5 months showed increasing correlation values after the 1970s (Fig. 12). In particular, the correlation values of chronology with precipitations in winter, spring, and early summer became more prominent with rising temperature.

4. Discussion

Ring width of *Q. liaotungensis* positively responded to temperature during the cooling period (1940–1969) in most of the months examined (Fig. 5a), indicating that temperature limited radial tree growth under these climatic conditions. Increasing correlation values between temperature and chronology further confirmed the importance of temperature on annual radial growth of *Q. liaotungensis* during the cooling period. In contrast, the correlation between chronology and precipitation weakened with decreasing temperature; this decline was especially obvious with spring and early summer precipitation (Fig. 13). These results are in accordance with the findings of Carrer and Urbinati (2006) and Coppola et al. (2012) on conifer tree species (*Larix decidua* Mill.) in the Italian Alps, which showed that the correlation shift was more consistent for the climate variables that primarily drive tree growth, whereas variables without significant influence on radial tree growth showed relatively stationary climate–tree growth relationships. However, the correlation of ring width and temperature has weakened following temperature rise since the 1970s (Fig. 6). Since then, the influence of precipitation on radial tree growth has started to increase (Fig. 13), which suggests that warming-induced drought stress has shifted as the limiting factor on the radial tree growth of *Q.*

Fig. 7. Pearson correlations between aggregated temperature and chronology of *Q. liaotungensis*. Each month represents the end of 3, 4 or 5-month analyzed seasons. Solid, dashed and dotted lines represent Bonferroni-corrected *p*-value levels of 0.05, 0.01, and 0.001, respectively.

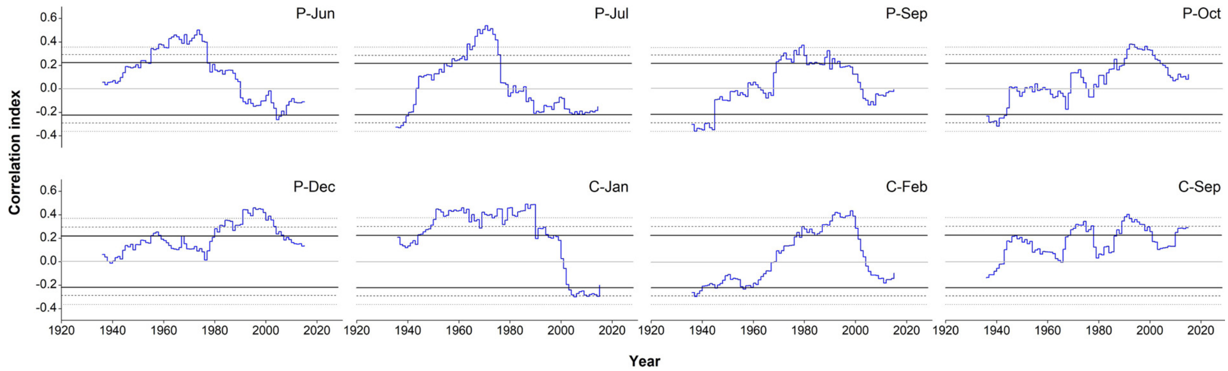

Fig. 8. Moving correlations between chronology and the temperatures of important months. Solid, dashed, and dotted lines represent Bonferroni-corrected *p*-value levels of 0.05, 0.01, and 0.001, respectively. Gray line represents the zero correlation value.

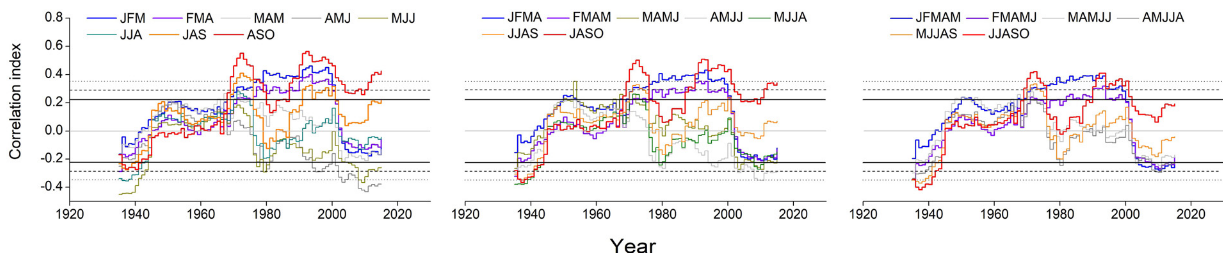

Fig. 9. Moving correlation values between chronologies of *Q. liaotungensis* and mean seasonal temperatures. Solid, dashed, and dotted lines represent Bonferroni-corrected *p*-value levels of 0.05, 0.01, and 0.001, respectively. Gray line represents the zero correlation value.

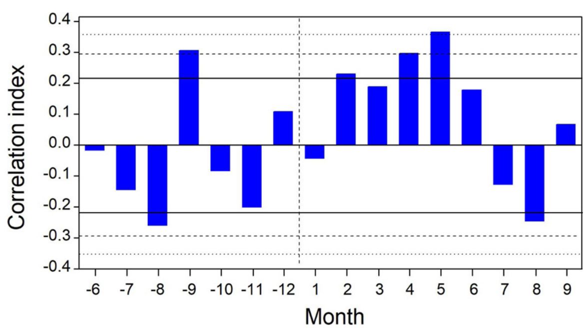

Fig. 10. Pearson correlation between chronology of *Q. liaotungensis* and precipitation for the period 1940–2016. The vertical dashed line represents the boundary of previous and current growing years. Horizontal solid, dashed, and dotted lines represent Bonferroni-corrected *p*-value levels of 0.05, 0.01, and 0.001, respectively. Numbers below the *x*-axis refer to the corresponding months from previous June (-6) to current September (9) in the correlation analysis.

liaotungensis. Our findings are consistent with reports from the Mediterranean forest (Shestakova et al., 2016), the boreal forest region of Alaska (Barber et al., 2000; D'Arrigo et al., 2005), and even forest–-tundra margins (Jacoby and D'Arrigo, 1995; Briffa et al., 1998). The positive correlation between ring width and temperature during the cooling period was attributed to the fact that temperature mainly controlled photosynthetic activity, which provides carbohydrates and energy for tree ring cell development and xylem formation, because precipitation was relatively high during this period (Fig. 2, *lower panel*). In contrast, temperature has become sufficient during the warming period, and water availability has become the main regulator determining tree radial growth. Our results match with the reports of Williams et al. (2011) on the change of climatic limiting factors affecting annual radial growth of white spruce trees in Alaska. *Q. liaotungensis* has a larger leaf area, and the energy budget through its leaves therefore is of great importance for tree growth. The mechanism for the weakened correlation between temperature and ring width may be through the influence of temperature on leaf-to-air vapor pressure deficit and tree evapotranspiration rate (Choat et al., 2012). When evaporative demand increases because of higher temperatures, leaf stomata tend to close to reduce water loss, resulting in lower CO_2 uptake and a decreased carbon assimilation rate (Lloyd and Farquhar, 2008), which ultimately hamper tree radial growth.

The moving correlation analysis between the chronology and temperature of aggregated months showed that the correlation values of chronology with temperature in all the aggregation forms increased with climatic cooling. The correlation values between chronology and summer temperature (June–July–August) began to decrease following increasing temperature since the 1970s, which leads us to hypothesize that the radial growth of *Q. liaotungensis* is very sensitive to the variation of summer temperature. However, the general variation of correlations of chronology with spring and autumn temperatures continuously increased after the 1970s, which indicated the possibility of a positive influence on the radial tree growth of *Q. liaotungensis* resulting from extending the growing season. A number of studies have reported that the warming climate has resulted in prolongation of the growing season in many places around the world (Menzel et al., 2006; Piao et al., 2007; Peng et al., 2011; Liu et al., 2013b). Coppola et al. (2012) reported the possibility of particular importance of a prolonged growing season on radial tree growth at treeline sites where tree growth is sensitive to climate change. Another possible explanation for the increasing importance of spring temperature on radial tree growth is that a warmer spring facilitates the melting of the frost soil layer, which increases soil water availability. As a result, roots grow faster, and developed root structures enable the uptake of more water and nutrients, which contribute to the early activation of xylogenesis and the formation of vessel structures, ultimately enhancing the carbon assimilation process (Lebourgeois et al., 2004).

Positive correlation values between chronology and winter temperature continuously increased after the 1970s, indicating that winter temperature started to exert significant impact on the radial tree growth of *Q. liaotungensis*. Increasing importance of winter temperature on radial tree growth can be explained by the fact that warmer winter

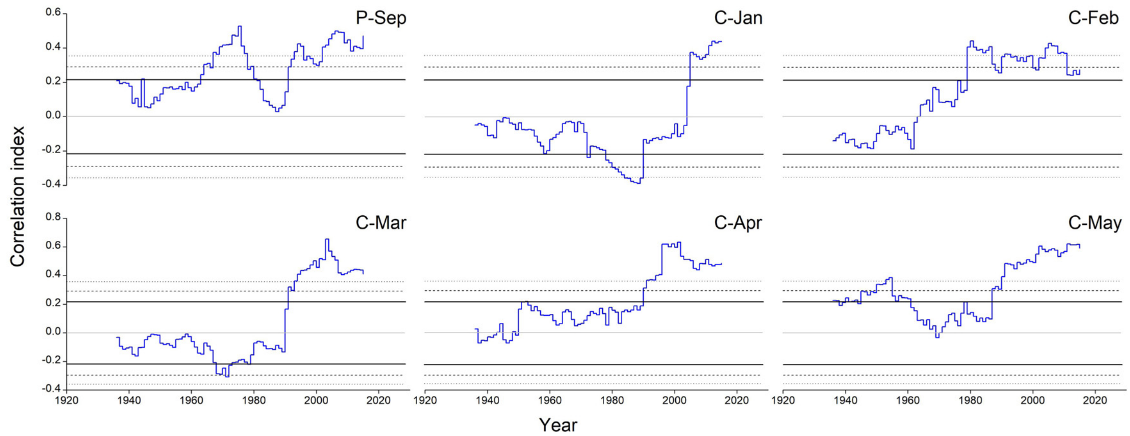

Fig. 11. Moving correlation values between chronologies of *Q. liaotungensis* and the precipitations of important months. Solid, dashed, and dotted lines represent Bonferroni-corrected *p*-value levels of 0.05, 0.01, and 0.001, respectively. Gray line represents the zero correlation value.

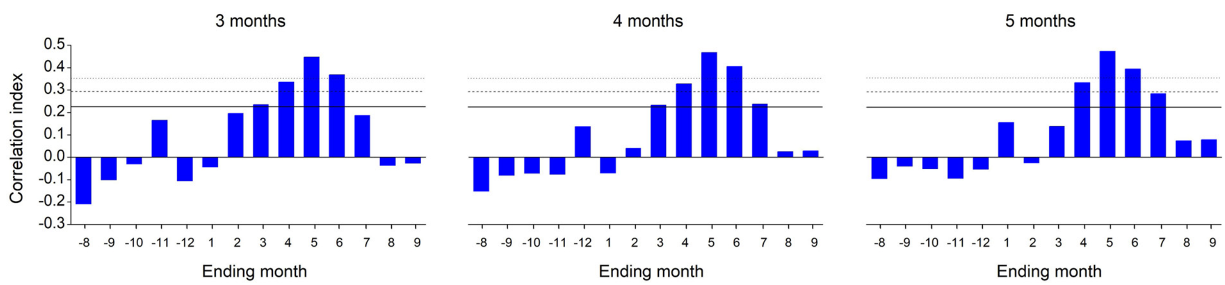

Fig. 12. Pearson correlations between aggregated precipitation and chronology of *Q. liaotungensis*. Each month represents the end of an analyzed 3, 4, or 5 month season. Solid, dashed, and dotted lines represent Bonferroni-corrected *p*-value levels of 0.05, 0.01, and 0.001, respectively.

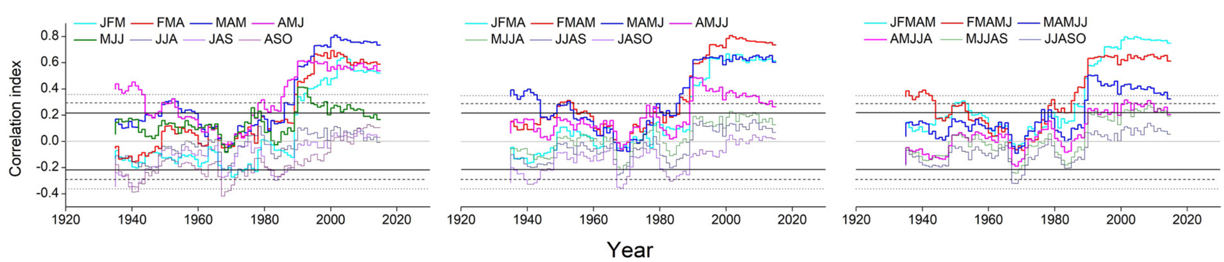

Fig. 13. Moving correlation values between chronology of *Q. liaotungensis* and mean seasonal precipitation. Solid, dashed, and dotted lines represent Bonferroni-corrected *p*-value levels of 0.05, 0.01 and 0.001, respectively. Gray line represents the zero correlation value.

temperature reduces cold damage on the fine roots of *Q. liaotungensis*, which are mostly distributed in the 30 cm upper soil layer (Qin, 2006). The energy stored in the parenchyma during previous-year tree growth that might otherwise be spent on the recovery of damaged roots or producing new roots in the following growing season (Secchi and Zwieniecki, 2011) would likely be used on the activation of the cambium layer instead, which facilitates carbon uptake and contributes to tree growth. The importance of the winter temperature on tree growth has also been reported by other studies (Bräuning, 2001; Pederson et al., 2004; Duan et al., 2012). The moving correlation analysis between chronology and precipitation showed that the correlation values started to increase after the 1970s, and the increase of correlation with spring and early summer precipitation was more obvious (Fig. 13). Spring and early summer are the most important periods when xylogenesis starts and vessel structures of *Q. liaotungensis* form; therefore, sufficient water availability not only contributes to but also guarantees nutrient transportation for these processes.

After the 2000s, the correlation values between chronology and temperature through all the months examined dramatically decreased (Fig. 9), and dropped below the level of significance except in autumn (August-September-October). Temperature increase in May, June and July probably exceeded the maximum threshold value for xylogenesis of *Q. liaotungensis*, and thus no longer contributed to radial tree growth. If warming continues, autumn temperature may also exceed the threshold value, radial tree growth of *Q. liaotungensis* may completely lose its connection with temperature, and decreasing regional precipitation may strengthen drought stress and cause the eventual decline of this tree species on Dongling Mountain.

5. Conclusions

Our results demonstrate the non-stationary characteristics of the climate–tree growth response of *Q. liaotungensis* on Dongling Mountain, Beijing. According to the climate–tree growth response analysis, temperature mainly controlled radial tree growth during the cooling period, whereas the influence of precipitation has increased with strengthening climate warming and has become the dominant regulator of radial tree growth. Our investigation revealed that climate warming has altered the relationship between climate and annual radial tree growth of *Q. liaotungensis* on Dongling Mountain. This change suggests that this area may undergo forest decline under the influence of warming-induced drought stress if climate warming continues.

Declaration of Competing Interest

The authors are fully agreed with the content of the manuscript, and they declare that they don't have any conflict of interest.

Acknowledgment

This work was funded by the National Key Research and Development Program of China (2016YFC0502105) and the National Natural Science Foundation of China (31971481). We appreciate Xian Cheng from Chinese Academy of Sciences for his technical support making the location map of study area.

References

R: A language and environment for statistical computing R Foundation for Statistical Computing, Vienna, Austria. URL. https://www.R-project.org/.

Adams, H.D., Guardiola-Claramonte, M., Barron-Gafford, G.A., Villegas, J.C., Breshears, D.D., Zou, C.B., Troch, P.A., Huxman, T.E., 2009. Temperature sensitivity of drought-induced tree mortality portends increased regional die-off under global change-type drought. Proc. Natl. Acad. Sci. U. S. A. 106 (17), 7063–7066.

Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D.D., Hogg, E.H.T., Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J., Allard, G., Running, S.W., Semerci, A., Cobb, N., 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. Forest Ecol. Manag. 259, 660–684.

Babst, F., Bouriaud, O., Poulter, B., Trouet, V., Girardin, M., Frank, D.C., 2019. Twentieth century redistribution in climatic drivers of global tree growth. Sci. Adv. 5 eaat4313.

Barber, V.A., Juday, G.P., Finney, B.P., 2000. Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. Nature 405 (6787), 668–673.

Biondi, F., Waikul, K., 2004. Dendroclim2002: a C++ program for statistical calibration of climate signals in tree-ring chronologies. Comput. Geosci. 30 (3), 303–311.

Bräuning, A., 2001. Combined view of various tree ring parameters from different forest habitats in Tibet for the reconstruction of seasonal aspects of Asian monsoon variability. Palaeobotanist 50, 1–12.

Breshears, D.D., Cobb, N.S., Rich, P.M., Price, K.P., Allen, C.D., Balice, R.G., Romme, W.H., Kastens, J.H., Floyd, M.L., Belnap, J., Anderson, J.J., Myers, O.B., Meyer, C.W., 2005. Regional vegetation die-off in response to global-change-type drought. Proc. Natl. Acad. Sci. U. S. A. 102 (42), 15144–15148.

Briffa, K.R., Schweingruber, F.H., Jones, P.D., Osborn, T.J., Shiyatov, S.G., Vaganov, E.A., 1998. Reduced sensitivity of recent tree-growth to temperature at high northern latitudes. Nature 391 (6668), 678–682.

Bunn, A.G., 2008. A dendrochronology program library in R (dplR). Dendrochronologia 26 (2), 115–124.

Bunn, A.G., Korpela, M., 2018. An introduction to dplR. The Comprehensive R Archive Network. . https://cran.biodisk.org/web/packages/dplR/vignettes/intro-dplR.pdf.

Cao, J., Zhao, B., Gao, L.S., Li, J., Li, Z.S., Zhao, X.H., 2018. Increasing temperature sensitivity caused by climate warming, evidence from Northeastern China. Dendrochronologia 51, 101–111.

Carrer, M., Urbinati, C., 2006. Long-term change in the sensitivity of tree-ring growth to climate forcing in Larix decidua. New Phytol. 170, 861–872.

Cerrato, R., Salvatore, M.C., Gunnarson, B.E., Linderholm, H.W., Carturan, L., Brunetti, M., Blasi, F.D., Baroni, C., 2019. A *Pinus cembra* L. tree-ring record for late spring to late summer temperature in the Rhaetian Alps, Italy. Dendrochronologia 53, 22–31.

Charney, N.D., Babst, F., Poulter, B., Record, S., Trouet, V.M., Frank, D., Enquist, B.J., Evans, M.E.K., 2016. Observed forest sensitivity to climate implies large changes in 21st century North American forest growth. Ecol. Lett. 19 (9), 1119–1128.

Choat, B., Jansen, S., Brodribb, T., Cochard, H., Delzon, S., Bhaskar, R., Bucci, S., Feild, T., Gleason, S., Hacke, U., Jacobsen, A., Lens, F., Maherali, H., Martı´nez-Vilalta, J., Mayr, S., Mencuccini, M., Mitchell, P., Nardini, A., Pittermann, J., Pratt, R., Sperry, J., Westoby, M., Wright, I., Zanne, A., 2012. Global convergence in the vulnerability of forests to drought. Nature 491, 752–755.

Cook, E.R., 1985. A Time Series Analysis Approach to Tree-ring Standardization. PhD thesis. University of Arizona, Arizona.

Cook, E.R., Kairiukstis, L.A., 1990. Methods of Dendrochronology: Applications in the Environmental Sciences. Kluwer Academic Publishers, Dordrecht.

Coppola, A., Leonelli, G., Salvatore, M.C., Pelfini, M., Baroni, C., 2012. Weakening climatic signal since mid-20th century in European larch tree-ring chronologies at different altitudes from the Adamello-Presanella Massif (Italian Alps). Quat. Res. 77 (3), 344–354.

D'Arrigo, R., Mashig, E., Frank, D., Wilson, R., Jacoby, G., 2005. Temperature variability over the past millennium inferred from northwestern Alaska tree rings. Clim. Dyn. 24 (2–3), 227–236.

Duan, J., Zhang, Q.B., Lv, L., Zhang, C., 2012. Regional-scale winter-spring temperature variability and chilling damage dynamics over the past two centuries in southestern China. Clim. Dynam. 39, 919–928. https://doi.org/10.1007/s00382-011-1232-9.

Fan, Z.X., Bräuning, A., Yang, B., Cao, K.F., 2009. Tree ring density-based summer temperature reconstruction for the central Hengduan Mountains in southern China. Glob. Planet. Change 65 (1–2), 1–11.

Fan, Z.X., et al., 2010. Tree ring recorded May–August temperature variations since A.D. 1585 in the Gaoligong Mountains, southeastern Tibetan Plateau. Paleogeogr. Paleoclimatol. Paleoecol. 296 (1–2), 94–102.

Feng, Y., Ma, K.M., Zhang, Y.X., Qi, J., 2009. Life history characteristics and spatial pattern of *Quercus liaotungensis* population in Dongling Mountain of Beijing, China. Chin. J. Ecol. 28 (8), 1443–1448 (in Chinese with English abstract).

Fritts, H.C. (Ed.), 1976. Tree Rings and Climate. Elsevier, London. https://doi.org/10.1016/B978-0-12-268450-0.X5001-0.

Girardin, M.P., Hogg, E.H., Bernier, P.Y., Kurz, W.A., Guo, X.J., Cyr, G., 2016. Negative impacts of high temperatures on growth of black spruce forests intensify with the anticipated climate warming. Glob. Change Biol. 22 (2), 627–643.

Gou, X.H., Gao, L.L., Deng, Y., Chen, F.H., Yang, M.X., Still, C.J., 2015. An 850-year tree-ring-based reconstruction of drought history in the western Qilian Mountains of northwestern China. Int. J. Climatol. 35 (11), 3308–3319.

Hoerling, M., Kumar, A., 2003. The perfect ocean for drought. Science 299 (5607), 691–694.

Holmes, R.L., 1983. Computer-assisted quality control in tree - ring dating and measurement. Tree Rings Bull. 43, 69–75.

Hughes, M.K., Wu, X.D., Shao, X.M., Garfin, G.M., 1994. A preliminary reconstruction of rainfall in north-central China since AD 1600 from tree-ring density and width. Quat. Res. 42 (1), 88–89.

IPCC, 2013. Summary for policymakers. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, US, pp. 1–28.

Jacoby, G.C., D'Arrigo, R.D., 1995. Tree ring width and density evidence of climatic and potential forest change in Alaska. Glob. Biogeochem. Cycle. 9 (2), 227–234.

Lebourgeois, F., Cousseau, G., Ducos, Y., 2004. Climate-tree-growth relationships of *Quercus petraea* Mill. stand in the Forest of Berce ("Futaie des Clos, Sarthe, France). Ann. Forest. Sci. 61, 361–372.

Li, Z.S., Liu, G.H., Wu, X., Wang, X.C., 2015. Tree-ring-based temperature reconstruction for the Wolong Natural Reserve, western Sichuan Plateau of China. Int. J. Climatol. 35 (11), 3296–3307.

Liang, E.Y., Shao, X.M., Liu, X.H., 2009. Annual precipitation variation inferred from tree rings since AD 1770 for the western Qilian Mts., northern Tibetan Plateau. Tree. Res. 65 (2), 95–103.

Lindholm, M., Eronen, M., 2000. A reconstruction of mid-summer temperatures from ring-widths of Scots pine since AD 50 in northern Fennoscandia. Geografiska Annaler: Series A. Phys. Geogr. 82 (4), 527–535.

Liu, H.P., Li, L., Sang, W.G., 2011. Species composition and community structure of the Donglingshan forest dynamic plot in a warm temperate deciduous broad-leaved secondary forest, China. Biodiver. Sci. 19 (2), 232–242 (in Chinese with English abstract).

Liu, B., Sun, Y.L., Wang, Y.C., Zhang, Y., 2013a. Monitoring and assessment of vegetation variation in North China based on SPOT/NDVI. J. Arid Land Resour. Environ. 27 (9), 98–103 (in Chinese with English abstract).

Liu, B., Li, Y., Eckstein, D., Zhu, L., Dawadi, B., Liang, E., 2013b. Has an extending growing season any effect on the radial growth of smith fir at the timberline on the southeastern Tibetan Plateau? Trees 27 (2), 441–446.

Lloyd, J., Farquhar, G.D., 2008. Effects of rising temperatures and (CO_2) on the physiology of tropical forest trees. Philos. Trans. R. Soc. Lond., B, Biol. Sci. 363, 1811–1817.

Ma, K.P., Gao, X.M., Yu, S.L., 1995a. On the characteristics of the flora on Dongling Mountain area and its relationship with a number of other mountainous floras in China. Bull. Botanic. Res. 15 (4), 501–514 (in Chinese with English abstract).

Ma, K.P., Huang, J.H., Yu, S.L., Chen, L.Z., 1995b. Plant community diversity in Dongling Mountain, Beijing, China: species richness, evenness and species diversities. Acta Ecol. Sin. 15 (3), 268–277 (in Chinese with English abstract).

Ma, F., Wang, S.Z., Feng, J.C., Sang, W.G., 2018. The study of the effect of tree death on spatial pattern and habitat associations in dominant populations of Dongling Mountain in Beijing. Acta Ecol. Sin. 38 (21), 7669–7678 (in Chinese with English abstract).

Martínez-Vilalta, J., Lloret, F., Breshears, D.D., 2012. Drought-induced forest decline: causes, scope and implications. Biol. Lett. 8 (5), 689–691.

McDowell, N.G., 2011. Mechanisms linking drought, hydraulics, carbon metabolism, and vegetation mortality. Plant Physiol. 155 (3), 1051–1059.

Menzel, A., Sparks, T.H., Estrella, N., Koch, E., Aasa, A., Ahas, R., Alm-Kübler, K., Bissolli, P., Braslavska, O., Briede, A., Chmielewski, F.M., Crepinsek, Z., Curnel, Y., Dahl, A., Defila, C., Donnelly, A., Filella, Y., Jatczak, K., Mage, F., Mestre, A., Nordli, Ø., Penuelas, J., Pirinen, P., Remisova, V., Scheifinger, H., Striz, M., Susnik, A., Van Vliet, A.J.H., Wielgolaski, F.-E., Zach, S., Zust, A., 2006. European phonological response to climate change matches the warming pattern. Glob. Chang. Biol. 12 (10), 1969–1976.

Pederson, N., Cook, E.R., Jacoby, G.C., Peteet, D.M., Griffin, K.L., 2004. The influence of winter temperatures on the annual radial growth of six northern range margin tree species. Dendrochronologia 22 (1), 7–29.

Peng, S.S., Chen, A.P., Xu, L., Cao, C.X., Fang, J.Y., Myneni, R.B., Pinzon, J.E., Tucker, C.J., Piao, S.L., 2011. Recent change of vegetation growth trend in china. Environ. Res. Lett. 6 (4), 044027.

Piao, S.L., Friedlingstein, P., Ciais, P., Viovy, N., Demarty, J., 2007. Growing season extension and its impact on terrestrial carbon cycle in the northern hemisphere over the past 2 decades. Glob. Biogeochem. Cycle 21 (3), GB3018.

Qin, J., 2006. Eco-physiological effect of *Populus davidiana - Quercus liaotungensis* mixed forests in Ziwulong forest area. Master thesis. Northeast Agricultural and Forestry University, Xi'an.

Regent Instrument Inc.http://www.regentinstruments.com/assets/windendro_analysisprocess.htm.

Secchi, F., Zwieniecki, M.A., 2011. Sensing embolism in xylem vessels: the role of sucrose as a trigger for refilling. Plant Cell Environ. 34 (3), 514–524.

Shestakova, T.A., Gutiérrez, E., Kirdyanov, A.V., Camarero, J.J., Génova, M., Knorre, A.A., 2016. Forests synchronize their growth in contrasting Eurasian regions in response to climate warming. Proc. Natl. Acad. Sci. U. S. A. 113 (3), 662–667.

Stokes, M.A., Smiley, T.L., 1996. An Introduction to Tree-ring Dating. Arizona University Press, Chicago.

Sun, S.Z., 1997. Geomorphologic and soil characteristics of Dongling Mountain. In: Chen, L.Z. (Ed.), Temperate Forest Ecosystem Structure and Function[M]. Science Press, Beijing, China (in Chinese).

Wigley, T.M., Briffa, K.R., Jones, P.D., 1984. On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. J. Clim. Appl. Meteorol. 23, 201–213.

Williams, A.P., Allen, C.D., Millar, C.I., Swetnam, T.W., Michaelsen, J., Still, C.J., 2010. Forest responses to increasing aridity and warmth in the southwestern United States. Proc. Natl. Acad. Sci. U. S. A. 107 (50), 21289–21294.

Williams, A.P., Xu, C.G., McDowell, N.G., 2011. Who is the new sheriff in town regulating boreal forest growth? Environ. Res. Lett. 6 (4), 526–533.

Williams, A.P., Allen, C.D., Macalady, A.K., Griffin, D., Woodhouse, C.A., Meko, D.M., 2013. Temperature as a potent driver of regional forest drought stress and tree mortality. Nat. Clim. Chang. 3 (3), 292–297.

Wu, X.P., Zheng, Y., Ma, K.P., 2002. Population distribution and dynamics of *Quercus liaotungensis, Fraxinus rhynchophylla* and *Acer mono* in Dongling Mountain, Beijing. Acta Botanic. Sin. 44, 212–223 (in Chinese with English abstract).

Xu, J., Wei, M., 2006. The climate change features in the last 100 Years. J. Capital Normal Univ. 27 (4), 79–82 (in Chinese with English abstract).

Yang, B., Qin, C., Wang, J.L., He, M.H., Melvin, T.M., Osborn, T.J., Briffa, K.R., 2014. A 3500-year tree-ring record of annual precipitation on the northeastern Tibetan Plateau. Proc. Natl. Acad. Sci. U. S. A. 111 (8), 2903–2908.

Yasue, K., Funada, R., Fukazawa, K., Ohtani, J., 1997. Tree-ring width and maximum density of *Picea glehnii* as indicators of climatic changes in northern Hokkaido, Japan. Can. J. Forest Res. 27 (12), 1962–1970.

Zang, C., Biondi, F., 2015. Treeclim: an R package for the numerical calibration of proxy-climate relationships. Ecography 38 (4), 431–436.

Zhang, Y.X., Ma, K.M., Qi, J., Feng, Y., Zhang, J.Y., 2009. Size structure and spatial pattern of *Quercus liaotungensis* population along elevation gradient in Dongling Mountain, Beijing. Acta Ecol. Sin. 29 (6), 2789–2796 (in Chinese with English abstract).

Zhang, Y.C., Wu, K., Yu, J.J., Xia, J., 2011. Characteristics of precipitation and air temperature variation during 1951–2009 in north China. J. Nat. Resources. 26 (11), 1930–1941 (in Chinese with English abstract).

Zhang, T.W., Zhang, R.B., Jiang, S.X., Bagila, M., Ainur, U., Yu, S.L., 2019. On the 'Divergence Problem' in the Alatau Mountains, Central Asia: a study of the responses of schrenk spruce tree-ring width to climate under the recent warming and wetting Trend. Atmosphere 10, 473.