Geografiska Annaler: Series A, Physical Geography

ISSN: 0435-3676 (Print) 1468-0459 (Online) Journal homepage: https://www.tandfonline.com/loi/tgaa20

Different responses of the radial growth of the planted and natural forests to climate change in humid subtropical China

Maowei Bai, Zhipeng Dong, Dai Chen, Huaizhou Zheng, Feifei Zhou, Xinguang Cao, Tinghai Ou & Keyan Fang

To cite this article: Maowei Bai, Zhipeng Dong, Dai Chen, Huaizhou Zheng, Feifei Zhou, Xinguang Cao, Tinghai Ou & Keyan Fang (2020): Different responses of the radial growth of the planted and natural forests to climate change in humid subtropical China, Geografiska Annaler: Series A, Physical Geography, DOI: 10.1080/04353676.2020.1769364

To link to this article: https://doi.org/10.1080/04353676.2020.1769364

GEOGRAFISKA ANNALER: SERIES A, PHYSICAL GEOGRAPHY
https://doi.org/10.1080/04353676.2020.1769364

Different responses of the radial growth of the planted and natural forests to climate change in humid subtropical China

Maowei Bai [a*], Zhipeng Dong [a*], Dai Chen [b], Huaizhou Zheng [a], Feifei Zhou [a], Xinguang Cao [a], Tinghai Ou [c] and Keyan Fang [a,c]

[a]Key Laboratory of Humid Subtropical Eco-geographical Process (Ministry of Education), College of Geographical Sciences, Fujian Normal University, Fuzhou, People's Republic of China; [b]National Forestry and Grassland Administration (National Park Administration), Beijing, People's Republic of China; [c]Regional Climate Group, Department of Earth Sciences, University of Gothenburg, Gothenburg, Sweden

ABSTRACT

China holds the world's largest area of planted forests, which play a crucial role in mitigating climate change. Knowledge gaps remain on the responses of the growth of planted forests to climate changes in China, particularly for their long-term changes. This study compared the long-term tree-ring growth patterns and their responses to climate between planted and natural forests. We developed four chronologies from two typical conifer species of *Pinus massoniana* and *Cunninghamia lanceolata* from planted and natural forests in humid subtropical China. One chronology is to our knowledge the longest chronology from planted forests in China spanning since 1944. Tree growths of both natural and planted forests are generally limited by summer drought due to the hot and dry summer in this area. In general, tree rings of the natural forests are more sensitive to climate than planted forests as indicated by higher inter-series correlations, which agree with previous studies. The natural forests are more drought sensitive wheareas the planted forests are relatively more limited by temperature. The *C. lanceolata* forests showed more significant correlations with the accumulated drought than *P. massoniana* for both the natural and planted forests.

ARTICLE HISTORY
Received 13 December 2019
Revised 9 May 2020
Accepted 12 May 2020

KEYWORDS
Planted forest; tree ring; humid subtropical China; drought; climate change

Introduction

The terrestrial ecosystem has the largest carbon pool relative to other carbon reservoirs of the earth. Forests contain approximately 60% of the carbon stored in terrestrial ecosystems (Strech and Scholz 2006; Hui et al. 2017), playing a key role in mitigating global climate change. The planted forests become more and more important due to the decline in natural forests and the increase in planted forests, particularly for China (Fang et al. 2001). Since the 1970s, a nationwide afforestation activity has made the planted forests in China now to be ranked the first in the world (Fang et al. 2001; Wang et al. 2001; Pan et al. 2004, 2011). Most of the planted forests in China are located in the south (Piao S et al. 2009). Fujian province holds the largest area of planted forests in China (47.1% of the total area of the planted forests) (The China State Forestry Administration 2014). Fujian province is located in humid subtropical China, an 'oasis' relative to the dry subtropics of the world (Figure 1) (Wang and Lin 2002; Chen et al. 2016). Moreover, Fujian province is one of the central production areas for *Pinus massoniana* and *Cunninghamia lanceolata* planted forests. Most of the planted forests in Fujian province are from the planted *C. lanceolata* forests followed by *P. massoniana*.

CONTACT Keyan Fang ✉ kujanfang@gmail.com

[*]Maowei Bai and Zhipeng Dong contributed equally to this work.

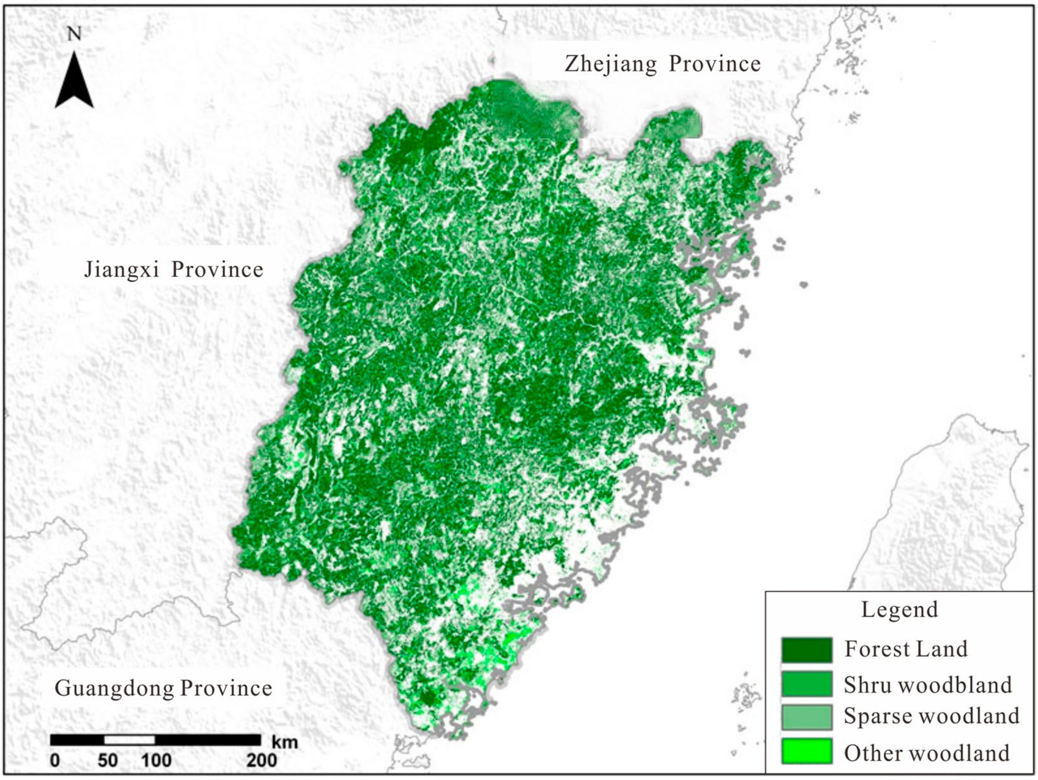

Figure 1 . Spatial distribution of forest resources in Fujian province in 2018.

In recent decades, numerous studies have been conducted on the planted forests (Bremer and Farley 2010; Zhou et al. 2013; Guo and Ren 2014; Sloan and Sayer 2015). However, it is still under debate about the differencing responses of natural and planted forests to climate change. For example, some researchers found that planted forests are more sensitive and vulnerable to droughts than natural forests, as indicated by larger amplitude of growth reductions and more severe crown defoliation after droughts than natural forests (Sánchez-Salguero et al. 2013). The planted forests experienced. The transpiration rate of planted forests is very close to their critical leaf water potentials and thus more sensitive to drought stress (Domec et al. 2015). However, other studies indicate that natural forests are more sensitive to climate change than planted forests (Fernández et al. 2009; Luo et al. 2016). For instance, natural forests have stronger stomatal control of leaf water potential and transpiration due to hydraulic limitations than planted forests, which may cause a higher climate-sensitive of natural forests than planted forests (Fernández et al. 2009).

Most of these studies were based on forest inventory, satellite and monitoring data, which often have a short duration of a few decades. Tree-ring data are good metrics of the long-term radial tree growth, which is an invaluable proxy for understanding the responses and adaption of tree growth to climate change in long-term periods and timescales. Tree-ring based studies on climate-growth relationships have been widely applied in humid subtropica China on natural forests (Shi et al. 2010; Chen et al. 2015; Li et al. 2016; Cai and Liu 2017). Unfortunately, no tree-ring based study has been conducted on the planted forests in humid subtropical China. This is largely because the planted forests in China are often 2–3 decades years old, which is not sufficiently long to extract robust climate-growth relationships. In this study, we are able to develop the longest tree-ring chronologies of planted forests in China with a duration of 73 years.

This tree-ring based study aims to: (1) identify the climate limiting factors of dominant planted trees of *P. massoniana* and *C. lanceolata* in humid subtropical China; (2) to examine whether the natural forests or planted forests are more sensitive to climate change.

Data and methods

Study region

Fujian province in humid subtropical China is dominated by East Asian monsoon with hot and humid climate occurring from March to August, and characterized by distinct seasonal contrast (Wang and Lin 2002; Wang et al. 2017). Influenced by the western Pacific subtropical high, drought in summer is another distinct feature of research region (Chen et al. 2012, 2013; Li et al. 2016). The records from the meteorological station of Yong'an (25.97° N, 117.35° E, elevation 206 m a.s.l.) show a mean annual temperature of 19.4°C and an annual total precipitation of 1556 mm. The coldest month (mean temperature of 9.4°C) and the warmest month (mean temperature of 28.3°C) are January and July, respectively. Eighty-seven percent of the annual precipitation falls during the growing season approximately from March to November. The mean annual frost-free period is 300 days while the mean relative humidity is 79–94%. The records from the meteorological station of Nan'ping (26.65° N, 118.17° E, elevation 126 m a.s.l.) show a mean annual temperature of 19.4°C and an annual total precipitation of 1644 mm. January (mean temperature of 9.4°C) and July (28.8° C) are the coldest and the warmest months, respectively. Eighty-eight percent of the annual precipitation falls during the growing season approximately from March to November.

Tree-ring sites of the natural and planted *P. massoniana* forests are located in the Sanming Nature Reserve (Figure 2). Natural *P. massoniana* forests mixed broad-leaved trees (*Castanopsis carlesii, Castanopsis kawakamii Hayata, Schima superba* and *Oak* et al.) and a rich understory shrubs (*Adinandra millettii, Rhododendron simsii* and *Pleioblastus amarus* et al.) and grasses (*Dicranopteris dichotoma* and *Miscanthus floridulus* et al.). Planted *P. massoniana* trees form pure forests with a small amount of understory vegetation of shrubs and grasses.

Tree-ring sites from Natural and planted *C. lanceolata* forests were located in the Mangdang Nature Reserve in Nan'ping city, which is ~66 km to the northwest of the *P. massoniana* sites (Figure 2). The natural *C. lanceolata* forests are in its late stage of succession mixed with various species (*PinustaiwaneusisHayata.*, *Taiwaniacryptomerioides*, *Casuarinaeguisetifolia.*, *HouttuyniacordataThunb.*, *PterocaryastenopteraC. DC.* and SalixbabylonicaL. et al.) and complex structure (Local Chronicles compilation committee of Fujian province 1998). The planted *C. lanceolata* trees remain to be in its early succession stage with a simple forest structure.

Tree-ring and climate data

Three to four cores per tree were taken at the breast height using increment borers. In total, we collected 88 tree-ring cores from 24 healthy natural *P. massoniana* trees and 75 tree-ring cores from 29 healthy planted *P. massoniana* trees. We collected 48 tree-ring cores from 22 healthy natural *C. lanceolata* trees and 127 tree-ring cores from 38 healthy planted *C. lanceolata* trees. The tree-ring chronologies were developed according to standard dendrochronological methods (Cook and Kairiukstis 1990). The tree-ring cores were mounted, air-dried and polished (Stokes and Smiley 1968), which were used for crossdating to assign calendar years to each ring. The quality of the crossdating was checked using the program COFECHA (Holmes 1983). The ring-width was measured to a 0.001 mm precision. To remove the age-related growth trend, we fitted a smoothed cubic spline curve with a 50% frequency cutoff equal to the mean length of all the series of the site. The tree-ring chronology is the mean of the dimensionless tree-ring indices via a biweight robust mean methodology (Cook 1985). To account for the potentially reduced signal strength with low sample size in, for example, its early portion, we used the

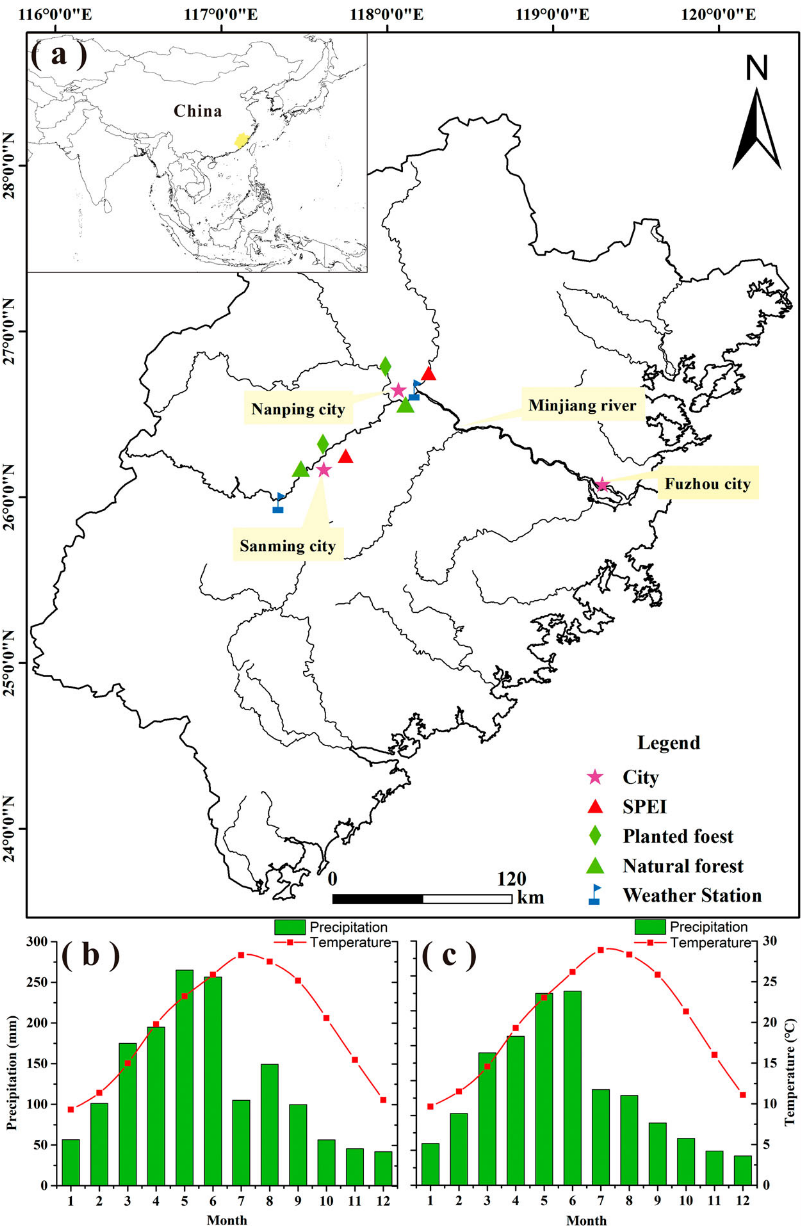

Figure 2 . Map showing (a) the locations of the tree-ring sampling sites, meteorological station and SPEI, (b) Monthly precipitation and temperature patterns in Yong'an (1951–2011), (c) Monthly precipitation and temperature patterns in Nan'ping (1951–2011).

statistic of the subsample signal strength (SSS) of higher than 0.85 to determine its reliable portion (Wigley et al. 1984).

We used the instrumental climate variables of monthly temperature, precipitation and percentage of sunshine from the nearest stations at Yong'an for *P. massoniana* sites and Nan'ping for *C. lanceolata* sites. We employed a drought metric of the Standardized Precipitation-Evapotranspiration Index (SPEI) (Palmer 1965; Linares and Camarero 2011; Williams et al. 2011), which has timescales from 1 to 48 months. The SPEI data used herein were derived from SPEI Global Drought Monitor with a 0.5 × 0.5 spatial resolution (Vicente-Serrano et al. 2010; Morice et al. 2012).

Analytical methods

Pearson correlations were calculated between tree-ring indices and climatic factors. To account for the influence of climate prior to the growing season, the correlations were calculated from the start of the previous growing season in March to the end of the current growing season in November. Twenty-one-year running correlation between climate and tree-ring data were further calculated to potential temporal changes of the climate-growth correlations. The correlations were additionally calculated for the first differenced data, which can measure the climate-growth relationships on interannual timescales. The first differenced data are calculated as the radio between residuals of adjacent years and their mean.

The composite analysis is also employed to evaluate the impact of extreme precipitation conditions on the radial growth of trees (Zhao et al. 2019). In application, we first classified monthly precipitation in the year with extremely high (values higher than the mean + SD) and low (values lower than the mean-SD) tree-ring widths into two groups, and calculated the means of each group. Second, the average monthly precipitation was standardized by min-maxnormalization. Finally, we calculated the residuals between the standardized average monthly precipitation of the two groups. High residuals indicated that extreme precipitation conditions often correspond to high radial growth of trees, and vice versa.

Results

Tree-ring characteristics of the planted and natural forests

The ring-width chronologies of the natural and planted *P. massoniana* forests cover the periods of 212 years (1801–2012) and 37 years (1976–2012), respectively (Figure 3). The reliable periods of the chronologies from natural and planted *P. massoniana* are 1843–2012 and 1976–2012, respectively (Figure 3). The *P. massoniana* chronology of the natural forests is one of the longest chronologies in central Fujian province (Dong et al. 2014). The ring-width chronologies span from 1941 to 2013 and from 1970 to 2013 for the natural and planted *C. lanceolata*, respectively (Figure 3). The reliable chronology of the natural and planted *C. lanceolata* are 1944–2013 and 1971–2013, respectively (Figure 3). The chronology of 73 years from the natural *C. lanceolata* forests is currently the longest one in China.

For *P. massoniana* forests, the inter-series correlations among tree-ring series are generally higher for natural ($r = 0.45$) forests than planted ($r = 0.27$) forests during their common period 1976–2012. Similarly, the natural *C. lanceolata* forests showed higher inter-series correlation ($r = 0.35$) than the planted ($r = 0.26$) ones. High inter-series correlation for the natural forests of both species suggests potentially higher climate sensitivity for natural forests than planted forests.

Climate-growth relationship

In general, the natural *P. massoniana* and *C. lanceolata* forests are more sensitive to climate than planted forests as indicated by higher significant climate-growth correlations (Figures 4 and 5). For *P. massoniana*, the natural and planted forests showed comparably significant correlations with temperature (Figure 3). However, the natural *P. massonian*a trees are clearly more significantly correlated with drought metric of precipitation and PDSI for natural forests than planted ones. For example, natural *P. massoniana* trees showed significant correlations with PDSI of which month and season, while there is no significant correlation with PDSI for planted *P. massoniana* trees (Figures 4).

Both natural and planted *C. lanceolata* trees showed a drought stress pattern with negative correlations with temperature but positive correlations with precipitation and PDSI (Figures 5). While the correlations with drought metric are particularly more significant for natural than planted forests. For temperature, the natural *C. lanceolata* trees showed significant correlations with temperature of which months and season, while the planted one only showed significant correlations in which months (Figures 5). The same is true for precipitation (Figure 5).

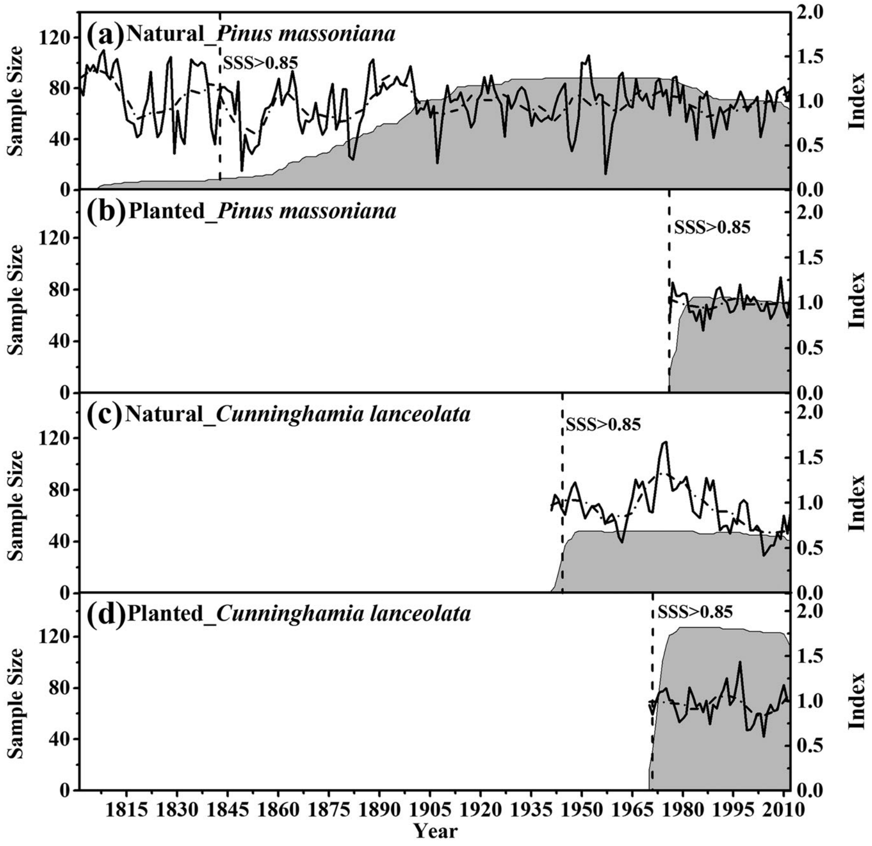

Figure 3. Tree-ring width chronologies from the (a) natural and (b) planted *P. massoniana*, and the (c) natural and (d) planted *C. lanceolata* (black curve), their 21-year low pass filter (dash dot curve), and their corresponding sample sizes (shaded area). The reliable portions of the chronologies were determined by the statistic of subsample signal strength (SSS) over 0.85.

Both the drought and winter coldness limit tree growth. But, the drought stresses are more restrictive to tree growth than temperatures, particularly for *C. lanceolata*. We further investigated the responses of tree rings to accumulate drought as indicated by the response timescales in SPEI (Figure 6). The natural *P. massoniana* chronology has more prompt responses to SPEI on timescales from 1 to 11 months (Figure 6a) relative to the planted *P. massoniana* chronology from 1 to 6 months (Figure 6b). Similarly, the natural *C. lanceolata* chronology has significant correlations with SPEI on longer timescales from 1 to 48 months (Figure 6c) than planted forests from 1 to 30 months (Figure 6d).

The natural forests are more sensitive to extreme climate conditions (Figure 7). For *P. massoniana*, the abnormally high tree growth corresponds to abnormally wet conditions in which month for natural forests, while less abnormally wet conditions are found for planted forests in which month. For the first-difference chronology of *P. massoniana*, the natural and planted forests correspond to comparably wet conditions in which months. So is the *C. lanceolata*.

Discussion

Higher climate sensitivity of natural than planted forests

Previous studies revealed both higher and lower climate sensitivities of natural than planted forests. Luo et al. (2016) indicate that a high climate sensitivity of natural than planted forests in sub-tropical region, other researches have found the opposite (Sánchez-Salguero et al. 2013; Domec et al. 2015).

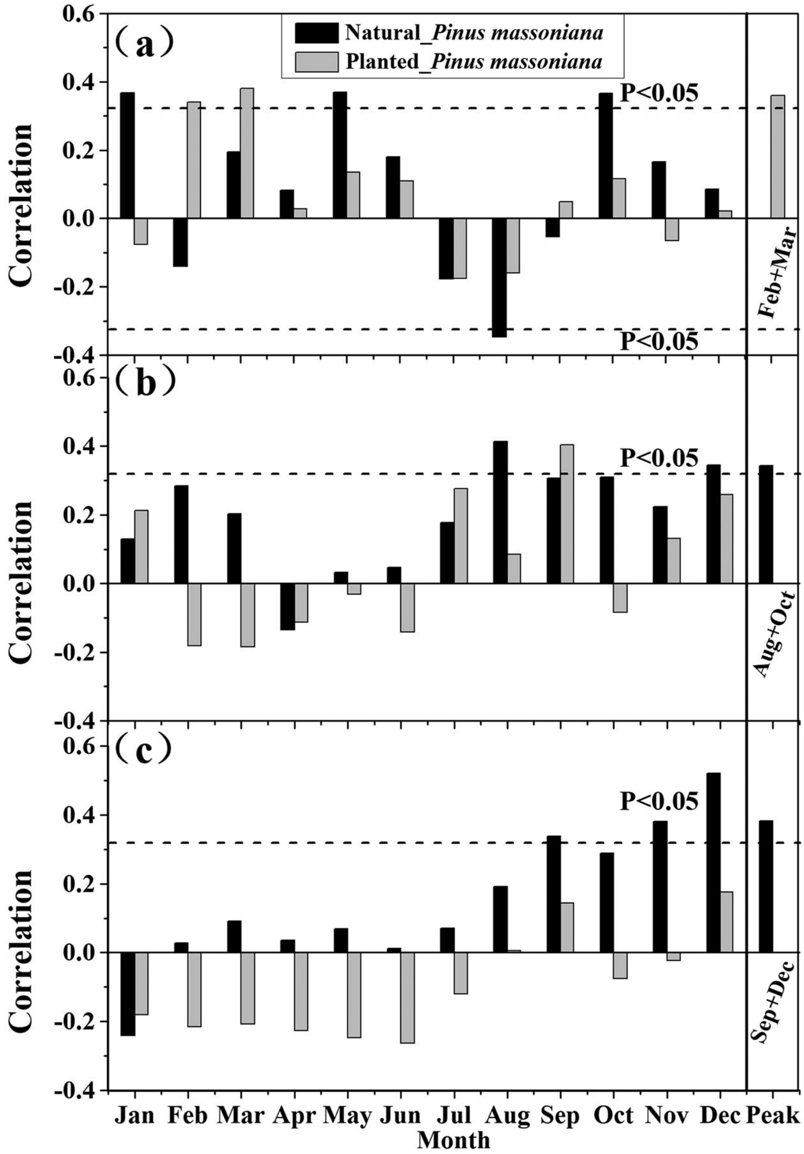

Figure 4. Correlations of the first differenced (a) temperature, (b) precipitation, (c) PDSI with the first differenced natural (black) and planted (gray) *P. massoniana* tree-ring chronologies from January to December of the current year. All the correlations were calculated during the common period between all chronologies and climate data from 1976 to 2012.

Natural forests have a stronger stomatal control of leaf water potential and transpiration, thereby indicating that natural forests are more sensitive to climate change than planted forests (Fernández et al. 2009). While the transpiration rate of planted forests is very close to their critical leaf water potentials (Domec et al. 2015), which suggesting that planted forests are more sensitive to droughts than natural forests. Therefore, the focus of the debate is the response of stomatal regulation and transpiration to soil water availability. The planted forests are often under managements and our sampled planted forests are under particularly strong managements. Forest managements in this site include plowing of the soil, thinning of the forests and the use of fertilizers and herbicides, which can largely reduce the climate sensitivity of the planted trees. For our hilly site, heavy precipitation in summer can easily flow away in planted forests due to its shallower soil caused by soil

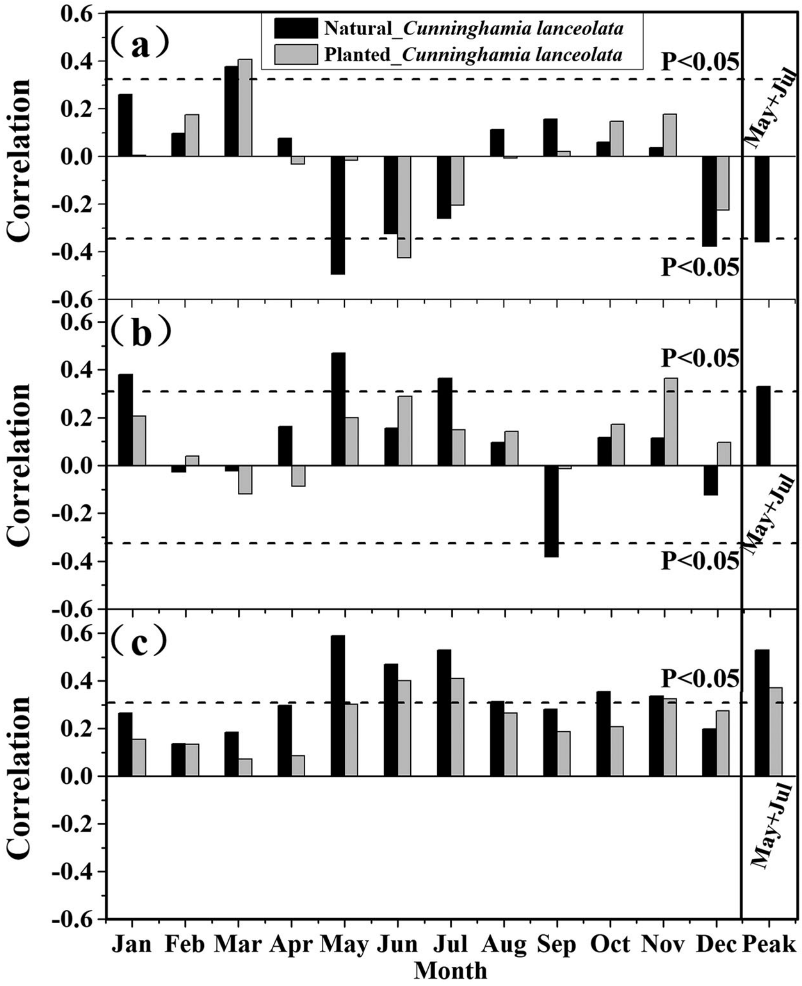

Figure 5. Correlations of the first differenced (a) temperature, (b) precipitation, (c) PDSI with the first differenced natural (black) and (gray) planted *C. lanceolata* tree-ring chronologies from January to December of the current year. All the correlations were calculated during the common period between all chronologies and climate data from 1976 to 2012.

erosion due to the thinning activities of the forests. The summer precipitation is difficult to be used for planted forests, causing a low sensitivity of planted forests to summer drought. This can be supported by a lower sensitivity to extreme summer precipitation and a lower sensitivity drought of planted forests than natural forests. A deeper soil condition for natural than planted forests can explain its higher sensitivity to accumulated drought conditions (Figure 6). It appears that the natural forests are well 'coupled' with climate change and can well adjust their growth conditions to adapt climate change, while the planted forests are more influenced by forest managements and may be vulnerable to climate stress.

Higher sensitivity accumulated drought for C. lanceolata *than* P. massoniana

Although both species are sensitive to drought, *P. massoniana* is less sensitive to accumulated drought than *C. lanceolata* (Figure 6). Actually, a more prompt response to drought was revealed to for *C. lanceolata,* which showed higher interannual variability than other conifer trees of the same region. *Pinus Linn* tree species often grow in extremely dry locations and often have shallow

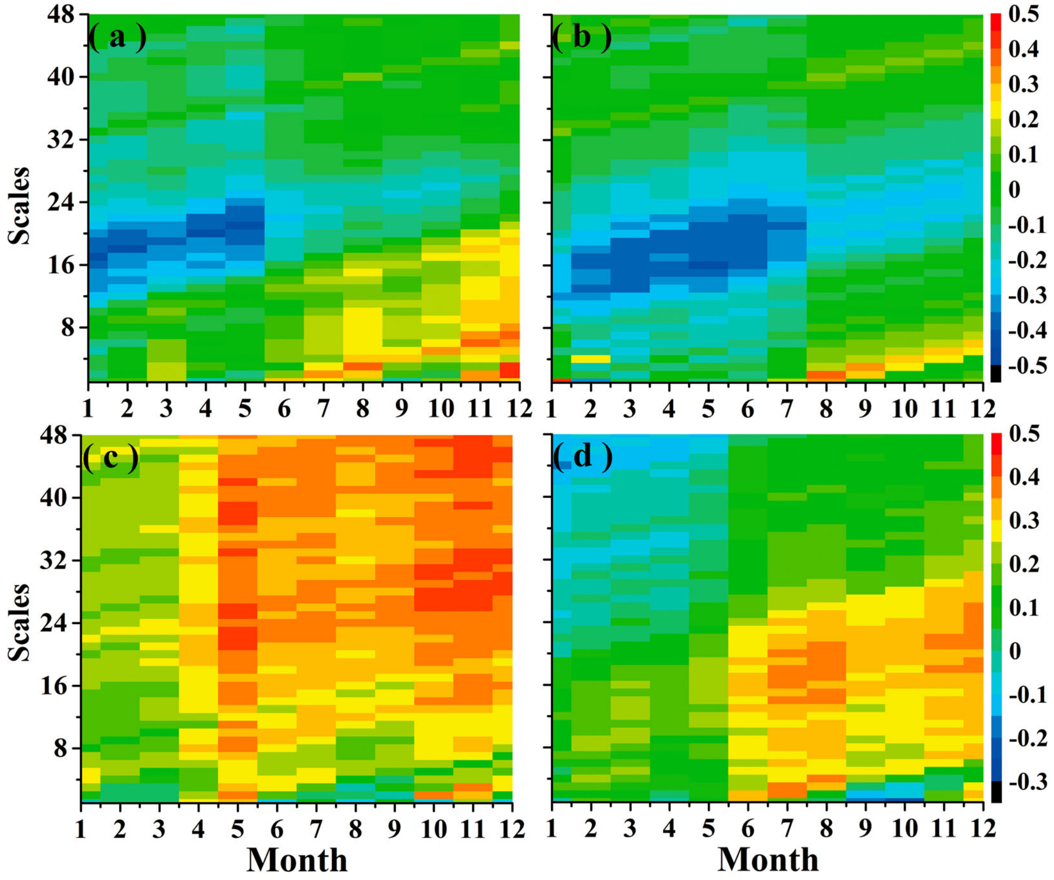

Figure 6. Correlations between the Standardized Precipitation Evapotranspiration Index (SPEI) for different times (from 1 month to 48 months) and the tree-ring chronologies for the (a) natural and (b) planted *P. massoniana*, and the (c) natural and (d) planted *C. lanceolata* from January to December of the current year.

soils. For example, *Pinus tabuliformis* often grow in south face mountains in north China that have higher evaporation and low soil moisture (Fang et al. 2009). *P. massoniana* is a pioneer species for ecological restoration as they adapt to dry conditions. It is readily understood that a more prompt response occur in dry sites where water cannot be retained in soil for long period. Actually, drought-sensitive *P. massoniana* is the most commonly used species for tree-ring based climate reconstructions in humid subtropical China (Chen et al. 2012). On the other hand, *P. massoniana* is more plastic than *C. lanceolata* (Kwesiga and Grace 1986; Portsmuth and Niinemets 2007). Drought stress enhanced the cell elasticity and drought tolerance of *P. massoniana*, whereas reduced the cell elasticity and drought tolerance of *C. lanceolata* (Wiilson et al. 1980; Bowman and Roberts 2006).

Conclusions

We developed four tree-ring chronologies of natural forests and planted forests, which contain the currently longest tree-ring chronology of planted forests in China. We argue that both the natural *P. massoniana* and *C. lanceolata* forests are more sensitive to climate relative to planted forests. Relative to temperature, natural forests are more particularly sensitive to long-term accumulate droughts than planted forests. In addition, extreme precipitations are more beneficial to extreme growths of natural forests than planted forests. Intensive forests managements and shallow soil conditions of the planted forests may account for their low sensitivity to accumulated drought and extreme

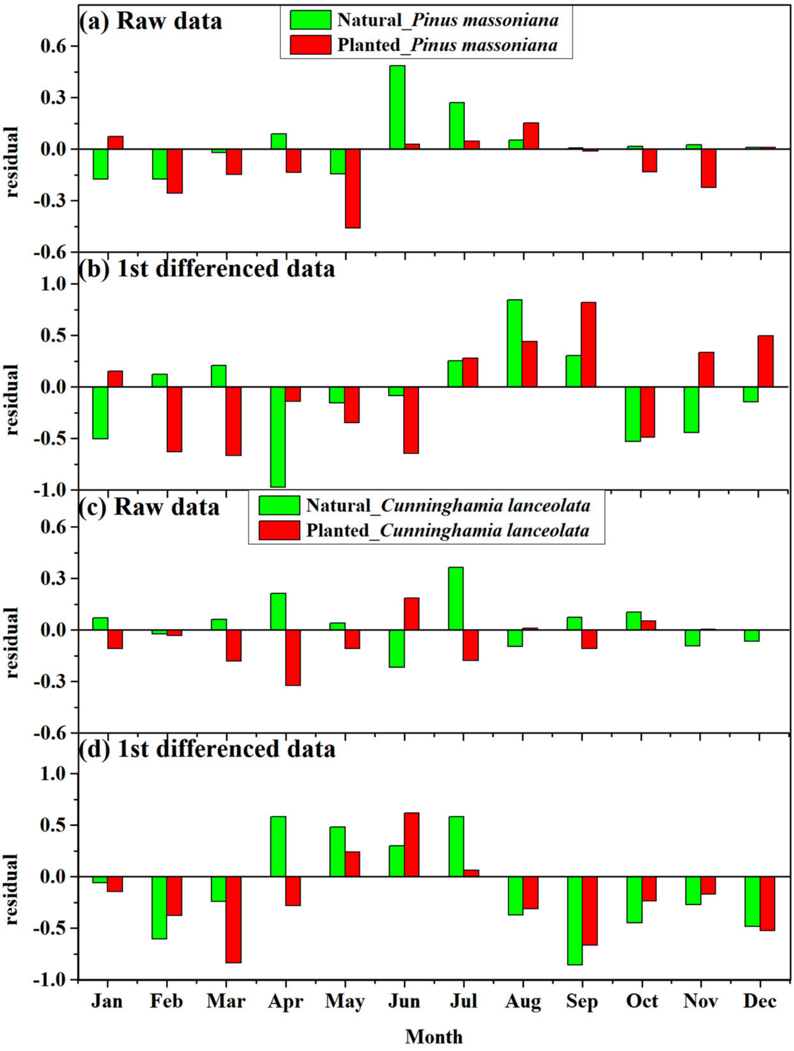

Figure 7. Map showing the composite analysis on the relationships between extreme tree growth and precipitation conditions. Classified monthly precipitation in the year with extremely high (mean + SD) and low (mean−SD) tree-ring widths into two groups and calculated their average. Average monthly precipitation was standardized by min-maxnormalization. Calculated the residuals between the standardized average monthly precipitation of the two groups. The standardized residuals were determined for the (a) raw and (b) first-differenced *P. massoniana* chronologies and the (c) raw and (d) first-differenced *C. lanceolata* tree-ring chronologies from January to December of the current year.

precipitations. This work improves our understandings on the species dependent responses of planted and natural forests to climate change in a tree-ring perspective. Future studies are needed to integrate tree-ring based studies of numerous areas and multiple species and other physiological and ecological studies on planted and natural forests to provide a comprehensive picture.

Acknowledgements

This research was funded by the National Science Foundation of China (41822101, 41772180, 41888101 and 41971022), Strategic Priority Research Program of the Chinese Academy of Sciences (XDB26020000), fellowship for the National Youth Talent Support Program of China (Ten Thousand People Plan), fellowship for Youth Talent Support Program of Fujian Province, the innovation team project (IRTL1705), and the Swedish Formas and VR projects.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This research was funded by the National Natural Science Foundation of China [41822101, 41772180, 41888101 and 41971022], Strategic Priority Research Program of the Chinese Academy of Sciences [XDB26020000], fellowship for the National Youth Talent Support Program of China (Ten Thousand People Plan), fellowship for Youth Talent Support Program of Fujian Province, the innovation team project [IRTL1705], and the Swedish Formas and VR projects.

Notes on contributors

Maowei Bai, male, born in 1991, mainly engaged indendroclimatic research.

Zhipeng Dong, male, born in 1989, mainly engaged in dendroclimatic research.

Dai Chen, male, mainly engaged in forest ecology research.

Huaizhou Zheng, male, mainly engaged in dendroclimatic research.

Feifei Zhou, male, mainly engaged in dendroclimatic research.

Xinguang Cao, male, mainly engaged in dendroclimatic research.

Tinghai Ou, male, mainly engaged in dendroclimatic research.

Keyan Fang, male, born in 1981, mainly engaged in dendroclimatic research.

ORCID

Maowei Bai http://orcid.org/0000-0002-9422-7286

References

Bowman WD, Roberts SW. 2006. Seasonal changes in elasticity in chaparral shrubs. Physiol Plant. 65(3):233–236.

Bremer LL, Farley KA. 2010. Does plantation forestry restore biodiversity or create green deserts? A synthesis of the effects of land-use transitions on plant species richness. Biodivers Conserv. 19(14):3893–3915.

Cai Q, Liu Y. 2017. Two centuries temperature variations over subtropical southeast China inferred from Pinus taiwanensis, Hayata tree-ring width. Clim Dyn. 5–6(48):1813–1825.

Chen D, Fang K, Li Y, Dong Z, Zhang Y, Zhou F. 2016. Response of Pinus taiwanensis growth to climate changes at its southern limit of Daiyun Mountain, mainland China Fujian Province. Sci China-Earth Sci. 59(2):328–336.

Chen F, Yuan Y, Wei W, Yu S, Wang H. 2013. Tree-ring response of subtropical tree species in southeast China on regional climate and sea-surface temperature variations. Trees-Struct Funct. 29(1):17–24.

Chen F, Yuan Y, Wei W, Yu S, Zhang T. 2012. Reconstructed temperature for Yong'an, Fujian, Southeast China: linkages to the Pacific Ocean climate variability. Glob Planet Change. 86-87:11–19.

Chen F, Yuan Y, Yu S, Zhang T. 2015. Influence of climate warming and resin collection on the growth of Masson pine (*Pinus massoniana*) in a subtropical forest, southern China. Trees. 29(5):1423–1430.

The China State Forestry Administration. 2014. Survey of China forest: the 8th national forest resources study. Beijing: China Forestry Press.

Cook ER. 1985. A time series analysis approach to tree ring standardization [dissertation]. Tucson: The University of Arizona.

Cook ER, Kairiukstis L. 1990. Methods of dendrochronology. Netherlands: Kluwer Academic Press.

Domec J, King JS, Ward E, Christopher Oishi A, Palmroth S, Radecki A, Bell DM, Miao G, Gavazzi M, Johnson DM, et al. 2015. Conversion of natural forests to managed forest plantations decreases tree resistance to prolonged droughts. Forest Ecol Manag. 355:58–71.

Dong Z, Zheng H, Fang K, Yan R, Zheng L, Yang Y. 2014. Responses of tree-ring width of *Pinus massiniana* in Sanming, Fujian Province to climate change. J Subtrop Res Environ. 2014:9(1):1-7.

Fang J, Chen A, Peng C, Zhao S, Ci L. 2001. Changes in forest biomass carbon storage in China between 1949 and 1998. Science. 292(5525):2320–2322.

Fang K, Gou X, Levia DF, Li J, Zhang F, Liu X, He M, Zhang Y, Peng J. 2009. Variation of radial growth patterns in trees along three altitudinal transects in north central China. IAWA J. 30(4):443–457.

Fernández ME, Gyenge J, Tomás S. 2009. Water flux and canopy conductance of natural versus planted forests in Patagonia. South America Trees. 23(2):415–427.

Guo Q, Ren H. 2014. Productivity as related to diversity and age in planted versus natural forests. Global Ecol Biogeogr. 23(12):1461–1471.

Holmes RL. 1983. Computer-assisted quality control in tree-ring dating and measurement. Tree-ring Bull. 44:69–78.

Hui D, Deng Q, Tian H, Luo Y. 2017. Climate change and carbon sequestration in forest ecosystems. New York: Springer.

Kwesiga F, Grace J. 1986. The role of the red/far-red ratio in the response of tropical tree seedlings to shade. Ann. Bot. 57(3):283–290.

Li Y, Fang K, Cao C, Li D, Zhou F, Dong Z, Zhang Y, Gan Z. 2016. A tree-ring chronology spanning 210 years in the coastal area of southeastern China, and its relationship with climate change. Clim Res. 67(3):209–220.

Linares JC, Camarero JJ. 2011. From pattern to process: linking intrinsic water-use efficiency to drought-induced forest decline. Glob Change Biol. 18(3):1000–1015.

Liu X, Local Chronicles Compilation Committee of Fujian Province. 1998. Fujian province natural atlas. In: The local Chronicles of the People's Republic of China. Fuzhou: Chronicle of Fujian Province; p. 127–129.

Luo H, Zhou T, Wu H, Zhao X, Wang Q, Gao S, Li Z. 2016. Contrasting responses of planted and natural forests to drought intensity in Yunnan, China. Remote Sens. 8(8):635–654.

Morice CP, Kennedy JJ, Rayner NA, Jones PD. 2012. Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: the HadCRUT4 data set. J Geophys Res-Atmos. 117. DOI:10.1029/2011JD017187

Palmer WC. 1965. Meteorological droughts. U.S. Department of Commerce Weather Bureau Research Paper. p. 45–58.

Pan Y, Birdsey RA, Fang J, Houghton R, Kauppi PE, Kurz WA, Phillips OL, Shvidenko A, Lewis SL, Canadell JG, et al. 2011. A large and persistent carbon sink in the world's forests. Science. 333:988–993.

Pan Y, Luo T, Birdsey R, Hom J, Melillo J. 2004. New estimates of carbon storage and sequestration in China's forests: effects of age-class and method on inventory-based carbon estimation. Clim Change. 67(2–3):211–236.

Piao S L, Fang J, Ciais P, Peylin P, Huang Y, Sitch S, Wang T. 2009. The carbon balance of terrestrial ecosystems in China. Nature. 458(7241):1009–1013.

Portsmuth A, Niinemets Ü. 2007. Structural and physiological plasticity in response to light and nutrients in five temperate deciduous woody species of contrasting shade tolerance. Func Ecol. 21(1):61–77.

Sánchez-Salguero R, Camarero JJ, Dobbertin M, Fernández-Cancio Á, Vilà-Cabrera A, Manzanedo RD, et al. 2013. Contrasting vulnerability and resilience to drought-induced decline of densely planted vs. natural rear-edge Pinus nigra forests. For Ecol Manage. 956–967.

Shi J, Cook E, Lu H, Li J, Wright W, Li S. 2010. Tree-ring based winter temperature reconstruction for the lower reaches of the Yangtze river in southeast China. Clim Res. 41(2):169–176.

Sloan S, Sayer JA. 2015. Forest resources assessment of 2015 shows positive global trends but forest loss and degradation persist in poor tropical countries. For Ecol Manag. 352:134–145.

Stokes MA, Smiley TL. 1968. An introduction to tree-ring dating. Tucson: University of Arizona Press.

Strech C, Scholz SM. 2006. The role of forests in global climate change: whence we come and where we go. Int Aff. 82 (5):861–879.

Vicente-Serrano SM, Beguería S, LópezMoreno JI. 2010. A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. J Clim. 23(7):1696–1718.

Wang XK, Feng ZW, Ouyang ZY. 2001. The impact of human disturbance on vegetative carbon storage in forest ecosystems in China. Forest Ecol Manag. 148(1):117–123.

Wang B, Lin Ho. 2002. Rainy season of the Asian–Pacific summer monsoon. J Clim. 15(4):386–398.

Wang M, Zheng Z, Man M, Hu J, Gao Q. 2017. Branched GDGT-based paleotemperature reconstruction of the last 30,000 years in humid monsoon region of Southeast China. Chem Geol. 463:94–102.

Wigley TML, Briffa KR, Jones PD. 1984. Average value of correlated time series, with applications in dendroclimatology and hydrometeorology. J Appl Meteorol Climatol. 23(2):201–234.

Wiilson JR, Ludlow MM, Fisher MJ, Schulze ED. 1980. Adaption to water stress of the leaf water relation of four tropial species. Aust J Plant Physiol. 7(2):207–220.

Williams AP, Ch X, McDowell NG. 2011. Who is the new sheriff in town regulating boreal forest growth? Environ Res Lett. 6(4):041004.

Zhao Z, Fang K, Cao C, Chen D, Liang X, Dong Z, Zhang P. 2019. Responses of the radial growth of the endangered species Keteleeria fortunei to climate change in southeastern China. Trees. 33(4):977–985.

Zhou J, Zhang Z, Sun G, Fang X, Zha T, McNulty S, Chen J, Jin Y, Noormets A. 2013. Response of ecosystem carbon fluxes to drought events in a poplar plantation in northern China. For Ecol Manag. 300:33–42.