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Comparisons of radial growth and tree-ring cellulose δ^{13}C for *Pinus sylvestris* var. *mongolica* in natural and plantation forests on sandy lands

Lining Song[a,b,c], Mingcai Li[a,b,c], Jiaojun Zhu[a,b,c] and Jinxin Zhang[a,b,c]

[a]CAS Key Laboratory of Forest Ecology and Management, Institute of Applied Ecology, Shenyang, China; [b]Liaoning Key Laboratory for Management of Non-commercial Forests, Institute of Applied Ecology, Shenyang, China; [c]Qingyuan Forest CERN, Chinese Academy of Sciences, Shenyang, China

ABSTRACT

To reveal the effects of water stress on the decline in introduced Mongolian pine (*Pinus sylvestris* var. *mongolica*) plantations, radial growth (basal area increment, BAI) and tree-ring cellulose δ^{13}C (carbon isotope composition) were compared in an introduced Mongolian pine plantation and a natural Mongolian pine forest during 1965–2009. Results showed that the BAI of plantation trees increased until 1990, followed by an abrupt decline from 1990 to 1996 and maintained a stable level thereafter. In contrast, no sign of decreased growth was found for natural trees. Tree-ring $\delta^{13}C_{corr}$ of plantation trees, corrected for atmospheric changes in δ^{13}C, significantly increased before and after 1990. However, no significant variations in tree-ring $\delta^{13}C_{corr}$ for natural trees before and after 1990 indicated no obviously water stress. Intrinsic water-use efficiency (iWUE, calculated from tree-ring δ^{13}C) significantly increased before and after 1990 for both forests. Significant negative relationship between BAI and $\delta^{13}C_{corr}$ or iWUE was found for plantation trees after 1990 when precipitation, Palmer Drought Severity Index (PDSI) and groundwater level decreased, suggesting water stress impact on growth. For plantation trees, PDSI was positively and negatively correlated with BAI and $\delta^{13}C_{corr}$, respectively, after 1990. For natural trees, BAI had no relationship with PDSI after 1990. These findings suggested that a decrease in PDSI (e.g. decreased precipitation and higher temperature) and groundwater level had made plantation trees face a more serious water stress compared with that of natural trees, which decreased tree growth. However, other stressors such as nutrient limitation may also contribute to growth decline.

Introduction

Desertification is regarded as one of the major environmental issues of the twenty-first century in semiarid and arid areas and has affected food security and environmental quality worldwide for centuries (Zheng et al. 2012). The total area of desertification in sand soil reached 1.53×10^9 ha in China by the end of 2000 (Zhu et al. 2005a). To prevent and control desertification, shelter forest systems have been established in areas subject to potential desertification. Mongolian pine (*Pinus sylvestris* var. *mongolica*), a geographical variety of Scots pine (*Pinus sylvestris*), is naturally distributed in the Daxinganling Mountains and the Hulunbeier Sand Plain of China (50°10′-53°33′N, 121°11′-127°10′E) and in parts of Russia and Mongolia (46°30′-53°59′N, 118°00′-130°08′E). Due to its hardy nature and suitability for dry environments, Mongolian pine was first introduced as the main tree species of shelter forest systems in the Keerqin sandy land, a semiarid sandy region in North China (Zheng et al. 2012).

Since the successful introduction of Mongolian pine into the Keerqin sandy land, the area of Mongolian pine plantations on sandy land has reached more than 3.0×10^5 ha in northern China (Zhu et al. 2006a). However, the Mongolian pine plantation in the original introduction area (Zhanggutai region in southeastern Keerqin sandy land) has shown progressive deterioration (such as top withered, lower growth and dead stems) since the beginning of the 1990s. In contrast, the natural forests of Mongolian pine in Hulunbeier sandy plains have remained healthy at the same growth stage as the plantation (Zhu et al. 2008). To explain the causes of plantation decline, many studies have been conducted, including the impact of water stress on survival, photosynthesis and stomatal conductance of seedling (Zhu et al. 2005b, 2008); water-use efficiency and plantation water sources (Song et al. 2015, 2016); foliar nutrient concentrations between natural and plantation forests (Zhu et al. 2006b) and so on. These studies have demonstrated that the lack of available water is one of the most important factors resulting in the decline in Mongolian pine plantations (Jiang et al. 2002; Zhu et al. 2008). However, these previous studies were short term, and the lack of knowledge about long-term variations in growth and ecophysiological traits impairs our understanding of the mechanisms underlying Mongolian pine plantation decline.

Tree-ring analysis offers a unique opportunity for understanding the response of trees to drought stress over decades, centuries and millennia (Sarris et al. 2013). Tree rings reflect the environmental conditions in which the tree grew during a particular year and can be used to indicate the growth and physiology of trees (Andreu et al. 2008). Additionally, an archive of stable carbon isotopes in tree-ring wood offers a useful tool for studies such as physical,

chemical and biological processes resulting in distinctive isotope effects over the lifetime of the tree (McCarroll & Loader 2004). The carbon isotope composition ($\delta^{13}C$) in tree rings has therefore been successfully used to estimate the drought response (water stress) and water-use efficiency of C_3 plants, as it provides a continuous, annually resolved record of environmental conditions during growth (Duquesnay et al. 1998; Xu et al. 2013). Thus, standard dendrochronological methods combined with carbon isotope analysis offer a physiologically based tool that is useful to decipher the long-term growth and ecophysiology of tree responses to changes in water availability (Silva et al. 2010).

The objectives of this study were as follows: (1) to compare long-term radial growth, tree-ring $\delta^{13}C$ and intrinsic water-use efficiency (iWUE, calculated from tree-ring $\delta^{13}C$) in plantation and natural forests on sandy lands and (2) to verify whether there was water stress with the decline in the plantation forests compared with the natural forests. To achieve the above two goals, two different Mongolian pine forests, the introduced Mongolian pine plantation in the southeast of Keerqin sandy land and the natural Mongolian pine forest in the Hulunbeier sandy land, were selected. The basal area increment (BAI) and tree-ring $\delta^{13}C$ during the periods from 1965 or 1975 to 2009 were measured and compared. In the discussion, we further explored the potential intrinsic reasons for water stress in the plantation.

Material and methods

Study area

The study was conducted at two sites: a plantation site (42° 43′N, 122°22′E, 224 m a.s.l.) and a natural site (48°15′N, 120°06′E, 864 m a.s.l.) (Figure 1). The former is located in the southeast of Keerqin sandy land, Zhanggutai region of Liaoning Province, China, which is the earliest introduced region for Mongolian pine. The annual mean precipitation and pan evaporation are 474 mm and 1700 mm, respectively. The annual mean temperature is 7.7 °C. The soil type is mobile sandy soil and soddy sandy soil (≥ 0.01 mm, 94.0%, < 0.01 mm, 6.0%), with an average soil depth of 107 cm. Dominant plant species are herbaceous plants such as *Agropyron cristatum, Arundinella hirta* and *Cleistogenes chinensis*. For Mongolian pine trees, 98% of roots were distributed within 1.0 m, but only 3–5 taproots can reach several meters in depth (4–5 m) (Zhu et al. 2005b). Plantation trees could use groundwater directly or indirectly through capillary rise in the plantation site (Song et al. 2016).

The natural site is located in Hulunbeier sandy land, Honghuaerji region of the Inner Mongolian Autonomous Region, China, which is the natural habitat for the Mongolian pine. The annual mean precipitation is 378 mm. The pan evaporation is 1174 mm. Annual mean temperature is −1.5°C. There are two major soil types, that is, pine sandy soil and soddy sandy soil (≥0.01 mm, 91.7%, <0.01 mm, 8.3%). Average soil depth is in the range from 0 to 90 cm. The plant species are more diverse than those in the plantation, and the dominant species under the canopy are shrubs such as *Filifolium sibricum, Stipa baicalensis, Festuca ovina* and *Carex pediformis* (Zhu et al. 2003, 2005a). In the natural forest site, the groundwater level (GWL) was more than 8.0 m (Zhao & Li 1963; Chen et al. 2012), suggesting that the natural trees could not use groundwater. Therefore, the GWL data in the natural site were not collected.

Field sampling and tree-ring measurements

In April 2010, 26 and 21 Mongolian pine trees were sampled in the plantation and natural forest, respectively. In the plantation site, the Mongolian pine stand was an even-aged forest with a stand density of 476 trees·ha^{-1} and was the oldest Mongolian pine stand in this region (52 years old, planted in 1958). In contrast, the Mongolian pine stand was an uneven-aged forest in the natural site, with a stand density of 1066 trees·ha^{-1}. The selected trees had an average diameter at breast height (DBH, 1.3 m) of 30.6 cm in the plantation, were 23–35 years old at DBH and had an average height of 9.5 m. The average DBH for the selected trees in the natural forest was 33.4 cm, and they were 37–46 years old at DBH and had an average height of 17.0 m. The plantation trees may have higher degree of pith eccentricity due to more rapid growth and greater wind (annual mean wind speed of 4.2 m·s^{-1}) compared with the natural trees (annual mean wind speed of 3.8 m·s^{-1}) (Warensjö 2003; Zhu et al. 2005b). Therefore, large difference in age at DBH would exist for the plantation trees at fixed position (e.g. south and north). Two cores (south and north) were extracted at breast height from each tree with an increment borer (5.1 mm, Suunto, Finland), mounted on wood boards and polished with sandpaper. All samples were visually crossdated using the methods described by Yamaguchi (1991). Tree-ring widths were measured to a precision of 0.001 mm using the LINTAB5 measurement equipment (Rinntech, Heidelberg, Germany). Tree-ring cross-dating was checked using COFECHA software (Holmes 1983). Then, all tree-ring series were detrended to remove non-climatic signals and maximize the climatic information in the series using a negative exponential function or linear curves in program ARSTAN. Several descriptive statistics commonly used in dendrochronology were also calculated (Table 1).

We calculated the mean ring width for all of the sampled cores to produce a final ring width series for the plantation
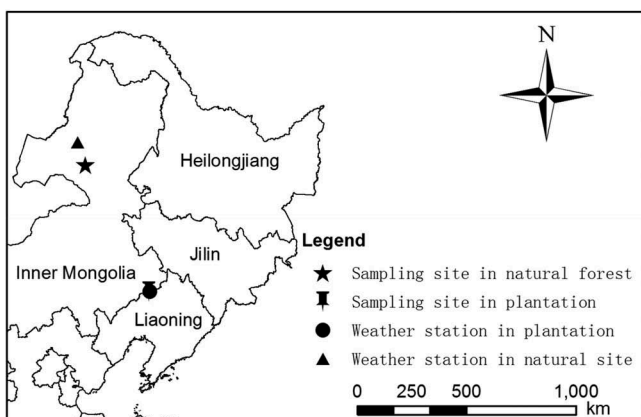

Figure 1. Sampling sites and weather stations for Mongolian pine forests. The black asterisk and triangle represent the sampling site and the weather station in the natural Mongolian pine forest (Natural), respectively. The black pin and circle represent the sampling site and the weather station in the Mongolian pine plantation (Plantation), respectively.

Table 1. Dendrochronological characteristics of the raw ring width data and ARSTAN mean chronology for the Mongolian pine trees in plantation and natural forests.

Characteristics	Plantation	Natural forest
Total years	35	45
Mean ring width	4.182	3.500
Mean index	0.951	0.969
Mean sensitivity	0.258	0.202
Standard deviation	0.306	0.208
Skewness	−0.291	−0.432
Kurtosis	3.395	3.979
First-order autocorrelation	0.408	0.243

($n = 52$) and natural trees ($n = 42$). Based on the tree-ring data, we calculated the mean basal area increment (BAI) of the 26 and 21 trees investigated for the plantation and natural trees by using the following formula (Silva et al. 2010):

$$BAI = \pi \times (R^2_n - R^2_{n-1}) \qquad (1)$$

where R is the radius of tree and n is the year of tree-ring formation. Converting radial increment (ring width) into BAI could remove the trend of decreasing ring width with increasing tree size (Granda et al. 2014).

$\delta^{13}C$ analysis

After dating and ring width measurement, three trees (two cores per tree) were chosen from each forest for $\delta^{13}C$ analysis, and the surfaces of tree cores were cleaned by means of an ultrasonic bath to remove remaining swarf, chalk or starch. Tree rings were separated year by year from each core using a scalpel under a stereomicroscope, and the rings from the same year per tree were mixed as one wood sample. Each wood sample was milled, packed in porous bags and then used to extract α-cellulose. The extraction of α-cellulose was conducted according to the method of Loader et al. (1997). The final α-cellulose samples were dried at 70°C for 48 h for isotope measurement.

The carbon isotope ratios ($\delta^{13}C$, ‰) were determined using an isotope ratio mass spectrometer (*MAT DELTA^{PLUS}XL*, Thermo Finnigan, San Jose, CA, US) and expressed by the following equation:

$$\delta^{13}C(‰) = \left[(R_{sample} - R_{standard})/R_{standard}\right] \times 1000 \qquad (2)$$

where R_{sample} and $R_{standard}$ are the isotope ratios ($^{13}C/^{12}C$) of samples and of the international standard Vienna-Pee Dee Belemnite (VPDB). The precision of the $\delta^{13}C$ measurement was checked with an internal standard material (glycine, −33.3‰, $n = 15$). Although we only used three trees from each forest in our isotopic analysis, this number is considered adequate to represent stand-level trends given the typical consistency of environmental signals reflected as isotopic ratios in tree rings (Gómez-Guerrero et al. 2013).

Intrinsic water-use efficiency (iWUE)

Following Farquhar et al. (1982), the iWUE was calculated using the equation:

$$iWUE = A/g = C_a[1 - C_i/C_a]0.625 \qquad (3)$$

where A is the rate of net photosynthesis, g is stomatal conductance to H_2O, C_i is intercellular CO_2 concentration,

C_a is the ambient air CO_2 concentration, and 0.625 is the relation among the conductance of H_2O compared to the conductance of CO_2 due to the higher molecular weight of the latter (0.625 gH_2O = gCO_2). To determine C_i, we used the following equation:

$$C_i = C_a\left[(\delta^{13}C_{plant} - \delta^{13}C_{air} + 1)/(b - a)\right] \qquad (4)$$

where $\delta^{13}C_{plant}$ and $\delta^{13}C_{air}$ are the plant and atmospheric C isotope composition, respectively, a is the discrimination against $^{13}CO_2$ diffusion through the stomata (4.4‰), and b is the net discrimination due to RuBisCo fractionation during carboxylation (27.0‰). The long-term C_a and atmospheric $\delta^{13}C$ from 1965 to 2003 were obtained from McCarroll and Loader (2004). Additional data (2004–2009) for C_a and atmospheric $\delta^{13}C$ were obtained from the Earth System Research Laboratory website (http://www.esrl.noaa. gov/gmd/about/aboutgmd.html).

Climate data

The summer temperature and annual precipitation data from 1965 to 2009 were obtained from the nearest stations in the two study sites, that is, the Zhanggutai meteorological station (42°70′N, 122°54′E, 228 m a.s.l.) for the plantation forest and Haila'er meteorological station (49°13′N, 119°45′E, 610 m a.s.l.) for the natural forest (Figure 1). To estimate the drought status for these two forests, growing season Palmer Drought Severity Index (PDSI) from 1965 to 2009 was collected from the Koninklijk Nederlands Meteorlogisch Instituut (KNMI) climate explorer (http://www.knmi.nl). The growing season PDSI in the plantation forest was the mean PDSI from April to October; however, the growing season PDSI in the natural forest was the mean PDSI from May to September due to different temperatures between the two sites (Zhao & Li 1963; Zhu et al. 2005b).

Data analysis

The raw $\delta^{13}C$ data were corrected for the decline in $\delta^{13}C$ in atmospheric CO_2 due to fossil fuel emissions following the method of McCarroll and Loader (2004) and Xu et al. (2013) (henceforth referred to as $\delta^{13}C_{corr}$). The corrected series were used for all statistical analyses. Temporal trends in summer temperature, annual precipitation, growing season PDSI, $\delta^{13}C_{corr}$ and iWUE, and the relationship between BAI and $\delta^{13}C_{corr}$ or iWUE were tested by simple linear regression. In addition, the BAI and $\delta^{13}C_{corr}$ relationships with summer temperature, annual precipitation and growing season PDSI were also tested using linear regression analyses. All of the statistical calculations and analyses were conducted using the SPSS software package, and all differences were considered significant at $P < 0.05$.

Results

Climate and groundwater level

Mean summer temperature increased significantly by 0.05 °C year^{-1} and 0.02 °C year^{-1} during the period 1965–2009 in the natural and plantation forests, respectively, ranging from 16.6 to 21.4 °C and from 21.0 to 24.8 °C (Figure 2(a)). Annual precipitation had no apparent trend during the period 1965–2009 in the natural forest
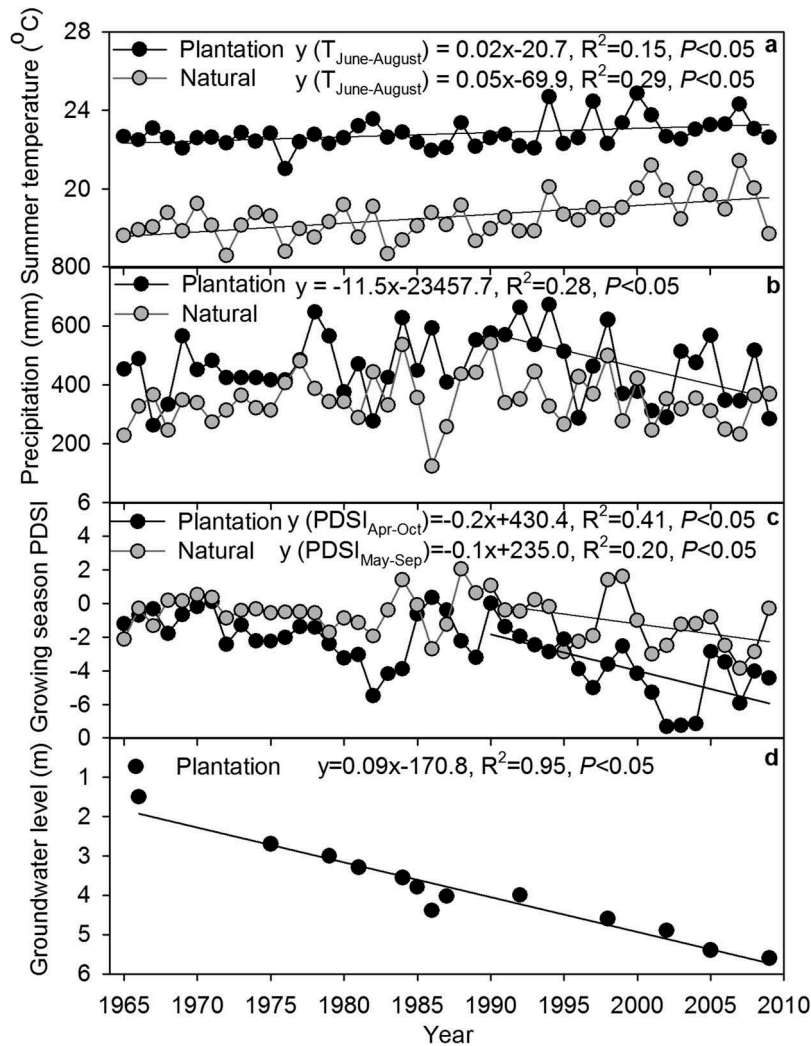
Figure 2. Annual variations in mean annual summer (June–August) temperature (a), precipitation (b), growing season Palmer Drought Severity Index (c) and groundwater level (d) from 1965 to 2009 in the plantation and natural forests. The groundwater level in the plantation forest was collected from Zheng et al. (2012), with permission from Elsevier.

and plantation, varying from 124.5 to 541.7 mm and from 262.3 to 672.0 mm, respectively (Figure 2(b)). However, a significant decrease in precipitation was found in plantation site after 1990. Growing season (May–September) PDSI in the natural forest did not show significant variation before 1990, varying from −2.7 to 2.1, whereas it decreased significantly after 1990, decreasing from 1.1 to −0.3 (Figure 2(c)). Similarly, growing season (April–October) PDSI had no apparent trend before 1990 in the plantation forest, ranging from −5.5 to 0.3, followed by a large and significant decrease from −0.01 to −4.4 for the period after 1990 (Figure 2(c)). In addition, the GWL declined from 1.5 to 5.6 m during the period 1965–2009 for the plantation site (Figure 2(d)), Zheng et al. 2012).

BAI, tree-ring $\delta^{13}C_{corr}$ and iWUE

There was a large difference in the trends of BAI during the last decades between the plantation and natural trees (Figure 3(a)). For the plantation trees, the BAI increased rapidly before 1990, followed by a rapid decrease during the period 1990–1996 and maintained a relatively stable level thereafter. In contrast, the BAI of the natural trees

increased gradually before 1990 and had no significant variations after 1990 (Figure 3(a)).

The tree-ring $\delta^{13}C_{corr}$ ranged from −24.0‰ to −20.6‰ and from −24.0‰ to −21.1‰ for the plantation and natural trees, respectively (Figure 3(b)). Overall, the tree-ring $\delta^{13}C_{corr}$ for the plantation trees increased significantly during the measurement period ($P < 0.05$, Figure 3(b)). The tree-ring $\delta^{13}C_{corr}$ for the plantation trees increased significantly before and after 1990, but no significant change trends were found for the natural trees before and after 1990 (Figure 3(b)). In addition, the iWUE of plantation and natural trees significantly increased during the measurement period ($P < 0.05$, Figure 3(c)). The iWUE of the plantation and natural trees also increased significantly before and after 1990, with the higher iWUE in plantation than in natural trees after 1990 ($P < 0.05$, Figure 3(c)).

For the plantation trees, the BAI was significantly positively correlated with tree-ring $\delta^{13}C_{corr}$ or iWUE before 1990, but significant negative correlation between BAI and $\delta^{13}C_{corr}$ or iWUE was found after 1990 (Figure 4(a and c)). However, no significant relationships between BAI and tree-ring $\delta^{13}C_{corr}$ or iWUE were observed for natural trees before and after 1990 (Figure 4(b and d)).
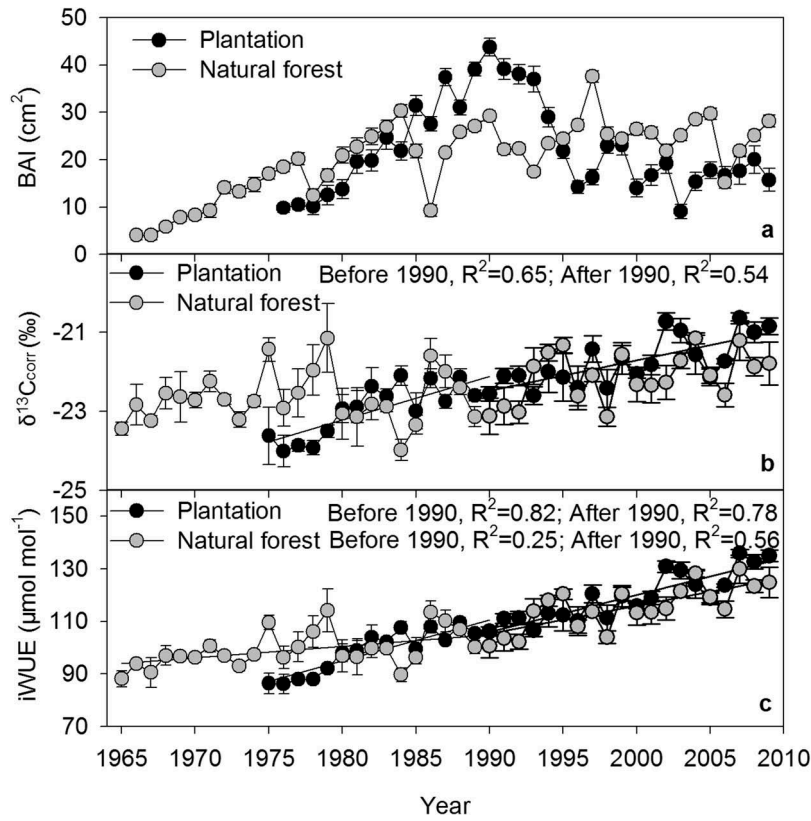
Figure 3. Basal area increment (a), $\delta^{13}C_{corr}$ (b) and intrinsic water-use efficiency (c) for the plantation forest during 1975–2009 and the natural forest during 1965–2009. Values represent mean ± SE.
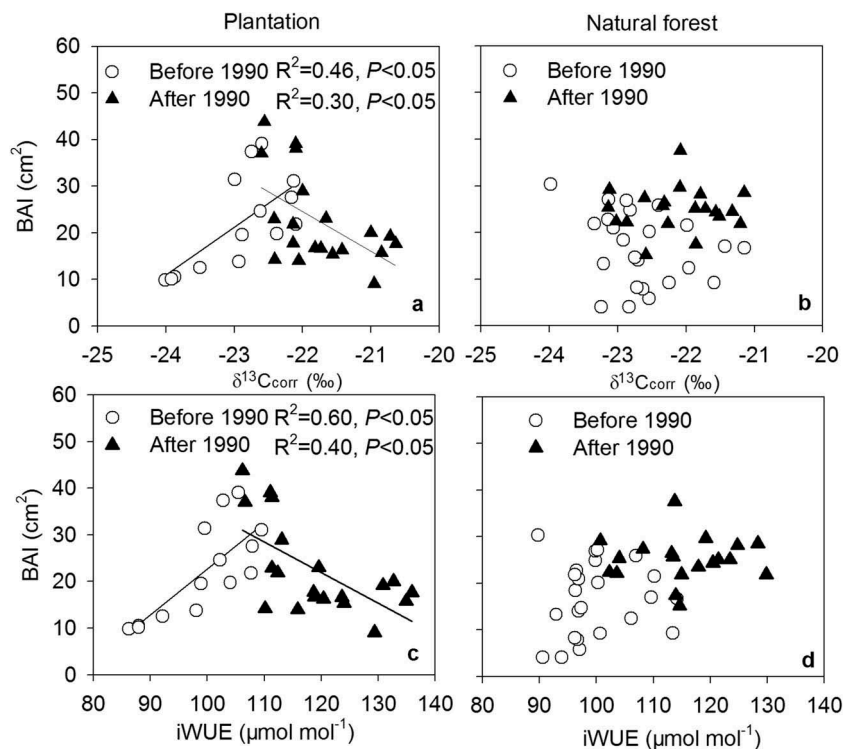

Figure 4. The basal area increment (BAI) relationships with $\delta^{13}C_{corr}$ and intrinsic water-use efficiency (iWUE) for the plantation (a and c) and natural forest (b and d), respectively.

Ring width–climate relationships

For the plantation trees, the ring width index was positively correlated with precipitation in February and negatively correlated with temperature in June (Figure 5(a)). However, for the natural trees, the ring width index was positively correlated with precipitation in July and negatively correlated with temperature in June (Figure 5(b)).
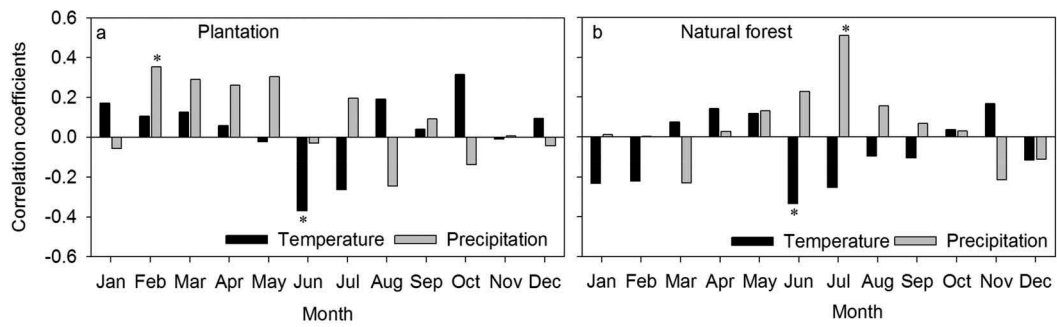
Figure 5. Correlations of tree rings with precipitation and temperature for plantation (a) and natural forests (b).
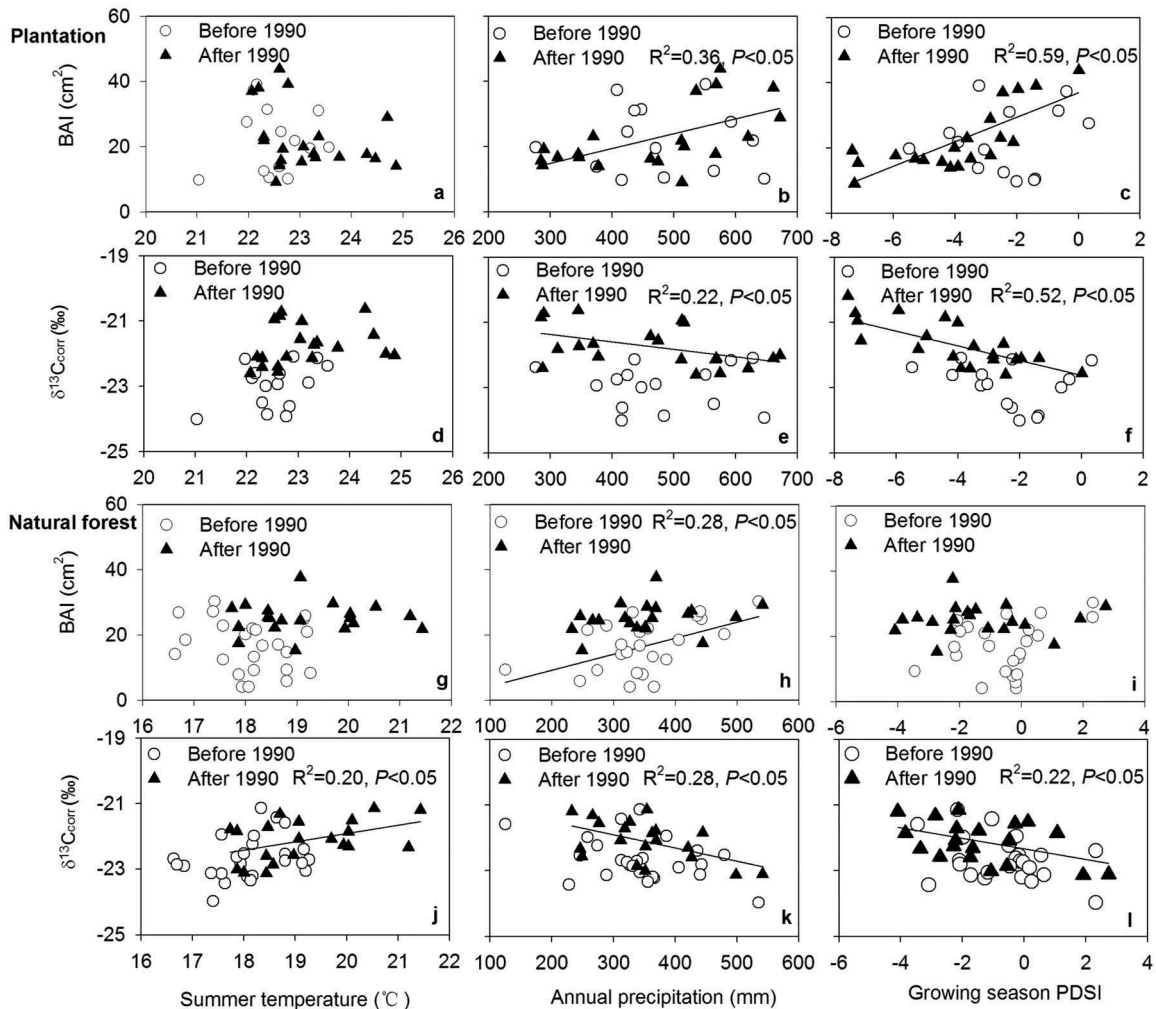

Figure 6. The BAI and $\delta^{13}C_{corr}$ relationships with summer temperature, annual precipitation and growing season Palmer Drought Severity Index (PDSI) in the plantation (a–f) and natural forest (g–l).

BAI, $\delta^{13}C_{corr}$ and iWUE relationships with summer temperature, annual precipitation and growing season PDSI

For the plantation trees, the BAI had no relationships with summer temperature before and after 1990 (Figure 6(a)), but the BAI was significantly positively correlated with precipitation and PDSI after 1990 (Figure 6(b,c)). Tree-ring $\delta^{13}C_{corr}$ had no significant relationships with summer temperature before and after 1990 (Figure 6(d)), but they had significant negative relationships with precipitation and PDSI after 1990 (Figure 6(e,f)). In contrast to the plantation trees, the BAI for the natural trees had no relationship with summer temperature, annual

precipitation or PDSI after 1990 (Figure 6(g–i)). Significant positive relationship between summer temperature and tree-ring $\delta^{13}C_{corr}$ was found after 1990, but the tree-ring $\delta^{13}C_{corr}$ had significant negative relationships with precipitation and PDSI after 1990 (Figure 6(j–l)).

Discussion

Differences in BAI, $\delta^{13}C_{corr}$ and iWUE between the plantation and natural trees

In this study, standard dendrochronological methods combined with carbon isotopic analysis were used to compare the long-term BAI, $\delta^{13}C_{corr}$ and iWUE between plantation

and natural Mongolian pine trees, highlighting different ecophysiological mechanisms such as responses to changes in water availability. Based on the variation in BAI and opposite relationships between BAI and $\delta^{13}C_{corr}$ or iWUE before and after 1990 for the plantation trees (Figures 3 and 4), we divided the data into two periods, for example, before 1990 and after 1990. For the plantation trees, increasing growth was observed before 1990, but BAI sharply declined during the period after 1990 (Figure 3(a)). This finding suggests that growth of the plantation trees had been limited by some stress factors (e.g. drought stress and increasing competition for resources among trees as stand development) during the period after 1990, which caused the decline in Mongolian pine plantations. These results resembled those found in boreal forest (Silva et al. 2010), which were thought to be under drought stress and competition between mature canopy trees (Duquesnay et al. 1998). However, no decline in growth for the natural trees (Figure 3(a)) suggested no persistent environmental stress for the natural trees (Granda et al. 2014).

In addition to the differences in tree growth between the two forests, a large difference in the $\delta^{13}C_{corr}$ between the two forests was observed (Figure 3(b)). Overall, the tree-ring $\delta^{13}C_{corr}$ of plantation and natural trees showed a significant increase during the measurement period (Figure 3(b)). The juvenile effect and drought stress were the main reason causing increase in tree wood $\delta^{13}C$ values (Loader et al. 2007). However, increase in tree wood $\delta^{13}C$ values inducing by juvenile effect generally lasts for a short period (<40 years), with only slight increase in $\delta^{13}C$ values of about 1‰ (Duquesnay et al. 1998; McCarroll & Loader 2004). In fact, the tree-ring $\delta^{13}C_{corr}$ for the plantation trees increased by 2.8‰ during the measurement period, but the tree-ring $\delta^{13}C_{corr}$ for the natural trees only increased by 1.1‰ during the measurement period. This indicated that water stress should be the main reason causing the increase in tree-ring $\delta^{13}C_{corr}$ for the plantation trees compared with the natural trees (Andreu et al. 2008; Eilmann et al. 2010; Sarris et al. 2013). Significant increasing trend in tree-ring $\delta^{13}C_{corr}$ of plantation trees was observed after 1990, but not found in the natural trees. During the period after 1990, the precipitation, PDSI and the GWL declined in the plantation site (Figure 2). These findings indicated that water stress induced increasing tree-ring $\delta^{13}C_{corr}$ for the plantation trees after 1990. Similar results have been reported by Eilmann et al. (2010) in *Pinus sylvestris* trees. They showed that the high $\delta^{13}C$ values of *Pinus sylvestris* trees reflect highly reduced stomatal conductance as a consequence of a chronic drought stress. This was also supported by the more close relationship between PDSI and $\delta^{13}C_{corr}$ in plantation trees compared with the natural trees (Figure 6(f and l)).

For the plantation trees, the BAI increased with increasing tree-ring $\delta^{13}C_{corr}$ before 1990 (Figure 4) with no significant relationship between BAI and PDSI (Figure 6(c)), indicating that the photosynthetic rate of the plantation trees increased before 1990. However, after 1990, the increasing tree-ring $\delta^{13}C_{corr}$ and decreasing BAI for the plantation trees, together with the negative relationship between tree-ring $\delta^{13}C_{corr}$ and PDSI, indicated that the plantation trees reduced stomatal conductance in response to increasing water stress at a low photosynthetic rate (Eilmann et al. 2010; Sarris et al. 2013). However, other

factors such as nutrient limitation may also influence the variations in tree-ring $\delta^{13}C$ and BAI after 1990 (the 31 years old of the studied plantation trees in 1990), because the nutrient content and foliar nutrient resorption efficiency for the plantation trees decreased obviously when the tree age was more than approximately 29 years old (Zeng et al. 2005; Zhu et al. 2005b). In addition, the natural trees increased or maintained their BAI values at consistent tree-ring $\delta^{13}C_{corr}$ before or after 1990 (Figure 3(b)). These findings are consistent with an expected growth increase in the absence of climatic stress because photosynthesis was stimulated, thus resulting in an enhanced CO_2 uptake (Granda et al. 2014).

Although the iWUE of trees in both forests significantly increased during the last few decades (Figure 3(c)), the higher increase and values in iWUE for the plantation trees than the natural trees after 1990 seem attributable to the warming and corresponding stronger water stress (McDowell et al. 2010; Hereş et al. 2014). Significant negative relationship between BAI and iWUE for the plantation trees after 1990 (Figure 4(c)) suggests that increasing iWUE over time may not translate into growth enhancements for the plantation trees. Similar results have been reported by other researchers for *Pinus sylvestris* (Voltas et al. 2013; Hereş et al. 2014) and *Pinus ponderosa* (McDowell et al. 2010). For example, Voltas et al. (2013) observed a clear trend of increasing iWUE and decreasing radial growth in *Pinus sylvestris* trees over a 25-year period of cumulative warming-induced drought stress. However, the natural trees maintained their BAI values at rising iWUE (Figures 3 and 4), indicating no obvious water stress for the natural trees.

The possible mechanism underlying the Mongolian pine plantation decline

Although there are many hypotheses that have been proposed to explain the decline in the Mongolian pine plantations, the lack of available water is considered to be the most important factor (Zheng et al. 2012). The apparent decrease in precipitation and growing season PDSI and the more close relationship between BAI and PDSI for the plantation trees during the period after 1990 (Figure 6) indicated that water stress limited the growth of the plantation trees compared with the natural trees. Temperature may not have directly affected the decline in tree growth due to no relationship between BAI and summer temperature (Figure 6(a)). However, the high summer temperature might have enhanced both evaporation and transpiration, causing more water stress for the plantation trees compared with the natural trees (Xu et al. 2013).

The water stress for the plantation trees was also related to the different durations of growth period compared with the natural trees. Most of the annual precipitation in both plantation (474 mm) and natural sites (378 mm) occurred during June and August. The higher correlation coefficient between tree growth and precipitation was observed in February–May for the plantation trees (Figure 5(a)). In this period (February–May), the precipitation is very limited, which may cause the conditions of water stress in plantation trees, especially in the high-growth period of May (Zhu et al. 2005b). However, due to the low temperature in the natural forest, most of the growth of Mongolian pine trees is concentrated from early June to early July (Zhu

et al. 2005b). This was supported by higher correlation coefficient between tree growth and precipitation of June–July (Figure 5(b)). In this period, there were ample snow-melt water and rainfall, so the growth of the natural trees was not affected by water availability. Apart from the precipitation and temperature effects, the decline in GWL may have been the most important factor affecting the water stress in the plantation forest (Zheng et al. 2012). When soil moisture does not meet the water requirement of tree growth, the roots of Mongolian pine trees in plantations absorb groundwater directly or indirectly through the capillary rise of groundwater (Song et al. 2016). However, the linear decrease in the GWL has been found since 1953, with a GWL of 4.0 m in 1990 (Figure 2(d)). The decreasing GWL would limit the growth of the plantation trees.

In addition to GWL, the progressive nutrition limitation may have been another reason for the decline in Mongolian pine plantations. Previous studies have shown that the decline in Mongolian pine plantations was correlated with low soil nutrient content (Jiang et al. 2002; Chen et al. 2009). Zhu et al. (2005b) observed that the plantation site had low nutrient content compared with the natural site and the nutrient content in the plantation site decreased obviously when the tree age was more than 28 years old. In addition, Zeng et al. (2005) reported that foliar nutrient resorption efficiency of the plantation trees significantly declined when tree age was more than 29 years old in the same study region. In 1990, the age of studied Mongolian pine plantations was approximately 31 years old, suggesting that the soil nutrient supply ability cannot meet the demands of pine growth more than 30 years old, due to a pure competition effect among trees as the stand development and the disturbance from local people (they collected the litter and carried out of the stands) (Zhu et al. 2005b). Whether progressive nutrient limitation was contributing to a decline in plantation tree growth remains to be further examined.

Conclusions

Large differences in the interannual variations of tree growth and tree-ring $\delta^{13}C_{corr}$ during the past decades were observed between the natural and plantation forests. Additionally, there is an apparent turning point around 1990 in tree growth, $\delta^{13}C_{corr}$ and their relationships with summer temperature, annual precipitation and growing season PDSI in the plantation forest. These findings suggest that water stress, together with nutrient limitation, affected tree growth and ecophysiological traits, which may be related to the decline in plantation forest. Although these findings provide information on long-term tree growth and ecophysiological traits during the period of decline of a plantation forest compared to a natural forest, further studies must be carried out to explore the distinct role of resource limitation (water vs. nutrients) in modulating the response of plantations to changes in water availability.

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