Impact of Competition on the Growth of Pinus Tabulaeformis in Response to Climate on the Loess Plateau of China

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Impact of competition on the growth of *Pinus tabulaeformis* in response to climate on the Loess Plateau of China

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Abstract: With climate change, understanding tree responses to climate is important for predicting trees' growth, and plant competition as a nonnegligible biotic factor plays a key role in such response. However, few studies have investigated how competition affects the response of *Pinus tabulaeformis*
plantations to climate. In our study, we investigated nine 29-year-old *P. tabulaeformis* plantation plots (three density gradients). The dendroecological method was used to analyze the impact of competition on trees’ response to drought and interannual climate variation. Stand density index was used to indicate the intensity of competition. The results showed that competition modified the climate-growth relationship. Competition increased trees’ sensitivity to drought but the relationship between competition and sensitivity to drought was nonlinear. The competition effect slightly increased under intense competition conditions. Additionally, competition reduced trees’ sensitivity to interannual climate variation. After 1999, the effect of competition was obvious. The sensitivity of small-diameter trees, especially those in middle- and high-density stands, declined. Thus, in the future these trees presumably may exhibit a reduced sensitivity to interannual climate variation and a greater sensitivity to drought.

**Keywords**: competition; drought; dendroecology; *P. tabulaeformis*; Loess Plateau

**Declarations**

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Impact of intraspecific competition on the growth of *Pinus tabulaeformis* in response to climate on the Loess Plateau of China

Abstract: With climate change, understanding tree responses to climate is important for predicting trees’ growth, and plant competition as a nonnegligible biotic factor plays a key role in such response. However, few studies have investigated how competition affects the response of *Pinus tabulaeformis* plantations to climate. In our study, we investigated nine 29-year-old *P. tabulaeformis* plantation plots (three density gradients). The dendroecological method was used to analyze the impact of competition on trees response to drought and interannual climate variation. Stand density index was used to indicate the intensity of competition. The results showed that competition modified the climate-growth relationship. Competition increased trees’ sensitivity to drought but the relationship between competition and sensitivity to drought was nonlinear. The competition effect slightly increased under intense competition conditions. Additionally, competition reduced trees’ sensitivity to interannual climate variation. After 1999, the effect of competition was obvious. The sensitivity of small-diameter trees, especially those in middle- and high-density stands, declined. Thus, in the future these trees presumably may exhibit a reduced sensitivity to interannual climate variation and a greater sensitivity to drought.

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1 Introduction

With climate warming, the frequency of drought is increasing, which has a great effect on ecosystems. Forests are vegetation types that are highly affected by drought. The response of forests to
drought is influenced by many factors such as damage by insects (DeLucia et al. 2012), nitrogen deposition (Hannusch et al., 2019), an increase in carbon dioxide concentration, and competition. The attack of insects may reduce trees resistance to drought or may increase the rate of tree mortality (Stephenson et al., 2019). A higher carbon dioxide concentration can increase water use efficiency, thus moderating water stress (Rahman et al., 2019). Competition is also a critical factor influencing tree growth and response to climate. Intense competition may exacerbate resource shortages. In a high-competition environment, serious water stress in drought years will affect the physiological activities of trees (Laurent et al. 2003; McDowell et al., 2011; Archambeau et al. 2020; Schmitt et al. 2020), cause growth decline (Jump et al., 2006), forest dieback (Rubio-Cuadrado et al., 2018; Gessler et al., 2018; Zhao et al., 2018), and even reduce biodiversity (Peng et al., 2011; Ploughe et al., 2019).

On the Loess Plateau of China, due to the high stand density there are large areas of dense plantations which are suffering from intense competition. Furthermore, the region might become more arid as the climate warms (Liu et al., 2018), which can further exacerbate plant competition, substantially influencing the sustainability of the local ecosystem. Therefore, understanding the competition effect on the response of the major species to climate is essential for forest management. However, how competition affects trees’ response to climate remains debatable.

Previous studies have shown contrasting results for competition effects on tree responses to drought. Some researches showed that competition increases with increasing stand density, which may exert a considerable impact on the performance of trees during arid spells. For example, Gleason et al. (2017) observed that competition exaggerated the water deficit and reduced tree resistance during a drought event. Similarly, Bottero et al. (2017) found that competition caused a growth decline in ponderosa pine and led to its low resilience. In addition, Zhang et al. (2015) concluded that intensive competition
may increase the mortality rate of trees with a weak ability to compete for resources. In contrast, Floyd et al. (2009) showed that the effect of competition on tree mortality in severe drought was not evident in *Pinus edulis* Engelm. stand. In addition, van Gunst et al. (2016) showed that in mid- to upper-elevation forests, mortality reduced in dense forests.

Competition also differs among trees of different sizes, which causes divergent responses to drought. Dominant trees with large diameters have stronger competitive abilities to obtain soil water and nutrients. These trees have a greater potential to tolerate water stress and are less sensitive to arid climates compared with small-diameter trees. Colangelo et al. (2017) showed that trees which dead in drought are smaller than living trees. However, in some cases, large trees demand more water. They receive more solar radiation and have longer hydrologic paths than small trees, which could increase the risk of hydraulic failure (McDowell et al., 2015). Thus they would be more sensitive to drought than small-diameter trees (Lingenfelder and Newbery, 2009; McDowell et al., 2015; Keyser et al., 2016; Zhang et al., 2018).

Additionally, various factors, such as micro-environment (Holtmeier et al., 2005), and age (Skubel et al., 2015), modulate the competition effect on trees’ response to drought as the climate warms. All of these factors combining with competition may alter trees responses to drought. For instance, favorable soil conditions can buffer the effect of arid climates (Schönbeck et al., 2020). Favorable soil conditions can also support more trees, forming high stand density compared with harsh soil conditions (Paoli et al., 2007). Water and nutrient demands increase as the stand grows, forming an intense competition environment. Dense forests also consume more nutrients and deteriorate soil conditions, leading to more intense competition (Qiu et al., 2019). This process leads to the effects of competition mixed with
soil conditions. Besides, the growth of trees with different ages may vary in response to climate (Wilson et al., 2004; Wang et al., 2009; Cavin et al., 2017; Gillerot et al. 2020; Jiao et al., 2020), which may be related to their different physiologies (Greenwood et al., 2008) and the competition they suffer from at different levels (Cescatti et al., 1998). These two factors would be mixed when analyzing the competition effect on the response of trees of different sizes.

For the competition effect on tree response to interannual climate variation, there are some different views. Some researchers have shown that trees living in a intensive competitive environment would be less sensitive to climate change (Fritts 1976). Ford et al. (2016) showed that as potential evapotranspiration (PET, which indicates the availability of energy for growth) and actual evapotranspiration (AET, which indicates the availability of energy and water for growth) increased, trees living under high competition and low competition displayed divergent growth. Zang et al. (2011) also showed that large-diameter tree growth had closer relationships with climate than that of small-diameter ones. However, Jiang et al. (2012) demonstrated that small-diameter trees, which were more suppressed by their neighbors, were more sensitive to climate. Moreover, Kerhoulas et al. (2011) revealed that the effect of competition on tree responses to climate was significant. Given the above debates above, the effect of competition on tree responses to interannual climate variation requires further exploration.

To deeply understand the effects of competition on tree responses to climate, an experiment was conducted in even-aged *Pinus tabulaeformis* Carr. plantations that have not been thinned after they were planted. *P. tabulaeformis* is one of the major planting species in northern China. This species has been widely planted on the Loess Plateau to prevent soil erosion due to its properties, such as drought
resistance and tolerance to barren soil (Zhou et al., 2007). However, because of the high stand density (initial stand density of 3300 stems/hm$^2$), the trees’ radial growth was slow, and some individuals are growth decline (Berger et al., 2004). Previous studies have demonstrated an increased drought vulnerability in dense pine plantations at xeric sites (Sánchez-Salgueiro et al., 2013). Thus, climate warming may also increase risks to these individuals and considerably impact their ecological functions. However, few studies have explored the impacts of competition on the response of *P. tabulaeformis* plantations to climate in the local areas. The main purposes of this study were to explore how competition affects the response of *P. tabulaeformis* to drought, and interannual climate variation. We hypothesized that: 1) competition increases the sensitivity of *P. tabulaeformis* to drought, and the effect may markedly increase with an increase in competition and that 2) the species sensitivity in response to interannual climate variation may gradually decrease due to increasing competition.

2 Materials and methods

2.1 Study site

The study site is located in Fangshan County, Luliang city, Shanxi Province, China (111°2′50″E-111°34′30″E, 37°36′58″N-38°18′27″N, Fig. 1). This area has a temperate continental climate. The average annual temperature is 7.3 °C, and the mean annual precipitation ranges from 440 to 650 mm (http://www.fangshan.gov.cn/zjfs/zrdl/201807/t20180709_732551.html). Higher precipitation often occurs in summer. Drought events have frequently occurred, especially in 1992, 1997, 1999-2000, 2005-2006, and 2015 (these years with mean standardized precipitation evapotranspiration index (MSPEI) values less than -0.5 representing a drought years, Fig. 2, Yu et al., 2014). In the 1990s, the dry period substantially affected the local forest ecosystem.
The predominant soil type of the local area is loess. Generally, the depth of soil is deep. Due to the differences in microenvironment, there are slight differences in soil properties in local areas. In April 2019, we investigated the properties of the soil. The physical properties of the soil are shown in Table S1 and Table S2 in the Supplementary Information.

Fig. 1 Location of the study site. The background of the main map is the normalized difference vegetation index (NDVI) in 2015. The NDVI data derived from MOD13Q1 was downloaded from the National Oceanic and Atmospheric Administration (NOAA).
Fig. 2 Change in MSPEI. MSPEI is the weighted average of the standardized precipitation evapotranspiration index (SPEI) at the 8-month scale.

2.2 Data collection

To analyze the effect of competition on the response of *P. tabulaeformis* to climate, 9 impermanent rectangle plots with similar elevations and aspects were set in even-aged pure *P. tabulaeformis* plantations in May 2018 (Table 1). All of these monoculture plantations were planted in the 1980s and were not thinned after being planted. These trees were approximately 29 years old when the experiment was conducted. We established three density gradients. In each density gradient, the plots were set in three stands with similar density (total of 9 densities). The average low stand density was 1208 stems/hm$^2$; the average middle density was 2275 stems/hm$^2$; and the average high density was 2989 stems/hm$^2$. In the plots, we measured the diameter at breast height (DBH) of every tree and recorded its coordinate. Since the diameter range was relatively large and, generally, trees of different sizes in a
stand responded differently to climate (Chen et al., 2012). Mérian et al. (2011) also showed that in even-aged stand (generally even-aged stand with single layer) it is divergent that trees of different size responses to climate. Thus, we sampled them in two size classes. Because the tree sizes of the low-density stands were larger than those of the high-density forest, the diameter was classified according to 65% of the maximum DBH. A DBH greater than 65% of the maximum DBH of the density was defined as the large-diameter class (the DBH range of low-density stands [14.3, 22] cm, of middle-density stands [13.8, 21.3] cm, and of high-density stands [12.2, 18.8] cm). In contrast, a DBH less than 65% of the maximum DBH but larger than 6 cm was defined as the small-diameter class (the DBH of low-density stands ranged [8, 14.2] cm, of middle-density stands [8, 13.7] cm, and of high-density stands [8, 12.1] cm). Two cores per tree were taken from at least 7 trees of every diameter class in each plot. Each core was drilled at breast height, and the direction was parallel to the contour line of the hillside. In total, we obtained 260 cores.

Table 1 Plot information

| Plot | Density (N/ha) | Mean DBH (cm) | DBH range (cm) | Longitude | Latitude | Slope degree | Aspect of slope | Elevation/m | Plot size |
|------|----------------|---------------|----------------|-----------|-----------|--------------|----------------|-------------|-----------|
| 1    | 1125           | 15.5          | 8.2-21.2       | 111°14′42″ | 37°43′45″ | 20°          | N37°           | 1296        | 20×20 m   |
| 2    | 1375           | 14.34         | 6.9-21         | 111°10′55″ | 37°47′21″ | 14°          | N28°           | 1461        | 20×20 m   |
| 3    | 1125           | 15.32         | 6.5-22         | 111°10′47″ | 37°46′52″ | 15°          | N49°           | 1430        | 20×20 m   |
| 4    | 2450           | 12.19         | 5.7-22.1       | 111°14′54″ | 37°43′24″ | 15°          | N350°          | 1339        | 20×20 m   |
| 5    | 2175           | 11.94         | 5.5-20.5       | 111°14′44″ | 37°43′27″ | 24°          | N22°           | 1291        | 20×20 m   |
| 6    | 2200           | 13.12         | 4.5-19.1       | 111°14′48″ | 37°43′27″ | 22°          | N33°           | 1305        | 20×20 m   |
| 7    | 2700           | 11.54         | 5.8-19         | 111°14′53″ | 37°43′24″ | 15°          | N298°          | 1335        | 20×20 m   |
2.3 Calculation of the competition index

To analyze the magnitude of competition, the stand density index (SDI) was used to indicate the competition pressure of a stand (Reineke 1933; Bottero et al., 2017). The SDI was calculated according to

\[ SDI = N \left( \frac{DBH_i}{DBH_r} \right)^{1.6} \]

where \( N \) is the number of trees per hectare, \( DBH_i \) is the quadratic mean DBH of all trees in per hectare, and \( DBH_r \) is the index diameter. In Europe, 25 cm was used (Pretzsch et al., 2005), while in China, generally the index diameter of 15 cm or 20 cm was chosen. Here we used 20 cm, which was used by Yan (2009).

2.4 Calculation of response indices and the tree ring width index

Increment cores were dried in a shaded area and then fixed and polished. All of the cores were measured with LINTAB 6 at 0.01 mm resolution. The COFECHA program was used to assess the cross-dating accuracy (Holmes, 1997).

The dated series were used to calculate the basal area increment (BAI) series by using the “dplr” package in R software (Bunn et al., 2020). Then, the BAI series was used to calculate indices for resistance (Rt), recovery (Rc), and resilience (Rs) (Trujillo-Moya et al., 2018). Rt can be characterized as the ability of trees to withstand a period of water deficit without showing a perceptible decrease in tree ring width (Rt<1 indicates a decline in growth). Rc describes the increase in tree ring width after a
drought compared with that in an arid year (i.e., $R_c > 1$ indicates an increase in growth after a drought).

$R_s$ is the ability to recover the growth level to that before a drought (here, $R_s = 1$ indicates complete recovery to predrought growth; otherwise the tree is still experiencing a legacy effect of the drought; Martínez-Vilalta et al., 2012; George et al., 2015). In this case, we studied the drought year 2015. Two years before and after the drought year were taken as background years for comparison. The equations are as follows:

\[
BAI = \pi \left( r_t^2 - r_{t-1}^2 \right) \tag{2}
\]

\[
R_t = \frac{Dr}{preDr} \tag{3}
\]

\[
R_c = \frac{BAI_{post}}{Dr} \tag{4}
\]

\[
R_s = \frac{postDr}{preDr} \tag{5}
\]

where $r$ is the radius of a tree; $t$ is the year of a tree ring. $Dr$, $preDr$ and $postDr$ mean BAI in drought, the average BAI of two years before and after a drought, respectively.

To analyze differences in response indexes among trees of different densities and diameters, the Mann-Whitney-Wilcoxon test was used (Hollander et al., 1973).

Additionally, the dated series were also used to calculate the tree ring width index chronology (TRWI) of the whole series and of different densities and diameter classes. To develop the standardized tree-ring width chronology (STRWI), the “ModNegExp” method was used to remove tree growth trends. The detrended series was then used to calculate TRWI by using beweight robust mean. In
addition, the residual chronology (RTRWI) was also established. This process was conducted by using the R package “dplr” (Bunn et al., 2020).

2.5 Climate data

Monthly climate data (i.e., precipitation and temperature) from 1989 to 2016 for the Lishi area close to the study site, were downloaded from the National Meteorological Science Data Center of China (http://data.cma.cn/). The data were used to calculate the SPEI. Potential evapotranspiration (PET) was calculated according to the Penman-Monteith equation. This process was conducted by using the R package “SPEI” (Santiago et al., 2017).

The Pearson correlation analysis was used to calculate the correlation between STRWI and RTRWI and SPEI at time scales of 1-12 months. The STRWI has a higher correlation with SPEI when compared with RTRWI, and the correlation is higher at the time scale of 8 months than that at other time scales (Supplementary Information Table S3, and Table S4). We then selected the 8-month SPEI (SPEI8), to calculate the MSPEI, which was calculated by the weighted mean of SPEI8 (Supplementary Information S1). The absolute value of the correlation coefficient between SPEI8 and RTRWI served as the weighting factor.

2.6 Analysis of trees responding to climate

To evaluate the effect of competition on trees’ response to drought, we developed a linear mixed-effect model for response indices (values were converted to a normal distribution by the square root, high th-root transformations, and reciprocal. The best method was selected by using “powerTransform” function in the “car” package) using the “nlme” package in R (Pinheiro et al.,
The random effect only considered the plot effect due to the superior results of the residual plot and qq plot of the model considering only plot effect versus those considering the effects of both the plot and the individual (Pinheiro et al., 2000). The model was expressed as follows:

\[ R = \alpha SDI + \beta + \varepsilon \] (6)

where \( R \) is the response index (\( Rt, Rc, Rs \)); \( SDI \) is a fixed effect, \( \beta \) is a random effect derived from the plot; \( \alpha \) and \( \varepsilon \) are the coefficient and error, respectively. All statistical analyses were conducted using R 3.5.1 (R Core Team 2018).

To study changes in trees’ response to climate variation, the response ability (relative basal area increment, RBAI) was calculated using the ratio of the BAI to the MSPEI for each density and diameter. Although the traditional method, moving correlation, has been widely used to test the change in the relationship of climate-growth, this method will reduce the length of the correlation series (at the beginning and the ending, the length of the correlation series equal to the window will loss). In our study, the length of the tree ring width was short. Thus, the moving correlation is not suitable for our study. We used the relative basal area increment (RBAI) to analyze the change in the response in the long term.

The RBAI is similar to the meaning of the climate effect on site productivity (Sharma et al., 2018). The response of tree growth (basal area increment, BAI) to climate is related to \( \alpha \), as shown by equation six. The larger the \( \alpha \), the more sensitive the tree is to climate conditions. The ratio (\( \alpha \), also RBAI) of the basal area increment to the climate index (MSPEI; in order to make RBAI larger than 0, we add 3 to the series of MSPEI) can indicate trees’ response to the interannual climate (equations six).
\[ BAI = \alpha \cdot MSPEI \] (6)

\[ \alpha = \frac{BAI}{MSPEI} \] (7)

where \( \alpha \) is the coefficient.

However, the volatility of RBAI is very large, which leads to an insignificant trend. Moving average is a method that was widely used to reduce fluctuation of a series (Merens, 2010). The five-year moving average of RBAI (MRBAI) was calculated to test the trend of RBAI. The Daniel test was conducted to test the significance of the trend before and after 1999 (the MSPEI decreased before 1999 and then increased, as shown in Fig. 2). We also analyzed the correlation between the standardized tree ring width chronology (STRWI, which has a closer relationship with climate than residual chronology, Supplementary Information Table S5 and Table S6) and SPEI8.

3 Results

3.1 Tree growth response to drought

Competition exerted significant impacts on tree responses to drought. As the density increased, competition increased, while Rt decreased. There were significant differences in Rt among densities (W=4360 \( P<0.01 \) [high-low density]; W=2897, \( P<0.001 \) [medium-low density]; W=5782, \( P<0.01 \) [high-medium density], Fig. 3a). Between diameters, the decline in the Rt of small-diameter trees was more obvious than that of the large-diameter class, and the difference increased from low density to high density (Fig. 3b).

In contrast, the change in the Rc was positively related to the increase in density. Among densities, the differences in the Rc were significant (middle-high density W=6114, \( P<0.01 \); low-high density
W=1629, \( P<0.01 \), Fig. 3c). Between diameters, the Rc of the small-diameter trees was larger than that of the large-diameter trees, and the difference was significant at the high density (W=1156, \( P<0.01 \), Fig. 3d), showing that the Rc of the small-diameter trees was more sensitive to the density increase than that of large-diameter trees.

The Rs slightly declined as the density increased. Among densities, the differences were significant (low-middle density W=4370, \( P<0.01 \); low-high density W=4391, \( P<0.01 \), Fig. 3e), and the differences between diameters were significant in the middle density stands (W=1422, \( P<0.01 \)) and high density stands (W=1556, \( P<0.01 \), Fig. 3f).

Fig. 3 Response indices among different densities and diameters. The letters L, M, and H represent low-, middle-, and high-density stands, respectively. The numbers 1 and 2 represent large- and small-diameter trees, respectively. Two asterisks indicate significant differences.
between diameters or densities ($P<0.01$), *, significant at $P<0.05$; **, significant at $P<0.01$. The orange dash line is the value equal to one.

3.2 Competition effect on trees' response to drought

As density increased, the competition increased, which heightened tree sensitivity in response to drought. The results of the linear mixed models showed that the significant effect of increased SDI caused the $R_t$ to decrease, and $R_c$ to increase in the whole series (Table 2). The form of the model (including $R_t^0.5$ and $R_c^{-0.25}$) also showed that the relationships between SDI and $R_t$ or $R_c$ were not linear (Fig.S1 and Fig.S3 also showed the nonlinear relationship between competition, and $R_t$ and $R_c$). It suggested that the rate of $R_t$ decline and the rate of increase in $R_c$ reduced with the increase of SDI. Thus, in dense stand trees resistance to drought and recovery from drought were not sensitive to the change in competition. The $R_s$ also decreased as the competition increased, but this relationship was not significant.

When the large- and small-diameter trees were separated, the models showed a similar pattern to that of the whole series. The marginal $R^2$ of $R_t$ and $R_s$ was larger in small-diameter trees than those in large-diameter trees (Table 2), and compared with large-diameter trees, the response indices showed more obvious changes for small-diameter ones (Fig. 3b, c and f). This result indicated that small-diameter trees were more sensitive to the increase in competition.

Table 2 Summary of the results of the linear mixed models for the competition effect on the response to drought. The whole series refers to all series combined for the analysis. Lc indicates the large-diameter class. Sc represents the small-diameter class. The bold type means that the estimation is significant.

| Variables | Intercept | SDI | Marginal $R^2$ | Conditional $R^2$ |
|-----------|-----------|-----|----------------|------------------|
|           |           |     |                |                  |

3.3 Growth response to inter-annual climate variation

Trees’ sensitivity to interannual climate variation was weakened by increased competition. The average correlation value between SPEI8 and STRWI was higher in the low-density stand than in the high-density stand (Fig.4). Before 1999, MSPEI declined (Fig.2), while BAI showed upward trends for all densities and diameters (Fig.5). The result showed that in their early stage their growth was not sensitive to the climate fluctuations. During this stage, the increased competition caused little effect on their sensitivity. Although competition became higher as trees have grown up, the MRBAI did not decline.
Fig. 4 Average correlation between STRWI and SPEI8 from low density to high density.

Fig. 5 Development of BAI. The basal area increment (BAI) is the average of each plot and diameter. The letters L, M, and H represent low-, middle-, and high-density stands, respectively. The numbers 1 and 2 represent large diameters and small diameters, respectively.

Fig. 6 Change in the MRBAI at different densities and diameters. The first period is 1990-1999. The
second period is 1999-2017. The letters L, M, and H represent low-, middle-, and high-density stands, respectively. The numbers 1 and 2 represent large diameters and small diameters, respectively.

After 1999, although the BAI did not show a decline, the upward trends gradually plateaued for small-diameter trees in high-density stands (Fig. 5). From low to high density, the trend of the MRBAI varied from upward to downward. For large diameters, the slope decreased from 5.67 to -0.44, while for the small diameters it decreased from 1.89 to -1.39 (Fig. 6). The result indicated that trees’ sensitivity of response to climate change was reduced by the increased competition. In low-density stands, trees’ sensitivity of response to long-term climate change increased, while in high-density stands it declined.

Additionally, the growth of large-diameter trees showed a higher correlation with interannual climate change. They were more sensitive to interannual climate change than small diameter trees (Fig. 4). During the whole period, when compared with large-diameter trees, small-diameter trees showed a slight increase in early stage (before 1999) and a steeper decline in the second stage (after 1999). Especially in middle- and high-density stands, small diameter tree MRBAI showed a significant decline (Fig.6), which indicates that small-diameter trees were greatly affected by increased competition. In middle- and high-density stands, small-diameter trees’ response to climate change was restricted by intensive competition.

4 Discussion

4.1 Competition effect on tree responses to drought

Competition exerts impacts on tree responses to drought. Our results also showed that competition significantly increased tree sensitivity to drought. With an increase in stand density, the competition for
water and nutrients became more intense (Vernon et al., 2018). Generally, increased competition worsens water resource shortages. We found a negative relationship between the SDI and Rt, which is consistent with the results of Gyenge et al. (2012) and Gleason et al. (2017). In addition, in our experiment, the effect of the SDI on the Rt was very weak for large-diameter trees, while the random effect had a considerable impact, which was mainly related to the weak competition from their neighbors and more favorable microenvironment. Large trees occupy a larger living space benefitting to developing their wider range of roots and larger crowns that could obtain more resources than smaller ones (Burt et al., 1985; Supplementary Information Fig. S4). In addition, their large stems could store more water for drought resistance (Phillips et al., 2003; Zang et al., 2014). Thus, they were less affected by competition.

However, some studies showed that large trees suffered greater impact and subjected to drought-induced mortality (Martínez-Vilalta et al., 2012; Bennett et al. 2015; Shenkin et al. 2018). Large trees had longer hydraulic path length and higher hydraulic resistance (Domec et al., 2008), which made them more vulnerable to hydraulic failure (Ryan et al., 2006). Besides, in their researches, the ages might differ between large- and small-diameter trees. In some cases, larger trees that suffer from weak competition are older than smaller ones that suffer from intense competition. Skubel et al. (2015) revealed that younger trees have more conservative water use strategies, while old trees showed greater variation in water use efficiency. Therefore, the effect might encompass both age and competition. Our experiment was conducted in an even-aged plantation, and the difference in height between the large- and small-diameter trees was not very obvious. Thus, the difference was mostly derived from the different growth rates and competition. Finally, in Martínez-Vilalta’s research, the species, Scots pine, is sensitive to high temperature. In contrast, P. tabulaeformis can tolerate drought
and high temperature (Zeng et al., 2005). Therefore, differences in species characteristics and forest structure may also lead to differences in responses to drought.

In general, the $R_c$ is negatively related to the $R_t$ (Gazol et al., 2017) but positively related to increasing competition. For some species, increased competition leads to the reduction of radial growth (Hui et al., 2018), but the trees have high proportions of latewood and relatively thicker cell walls. And the tree with low growth rate also has low wood density and high hydraulic conductivity, which indicate a low susceptibility of suffering from hydraulic failure (Carnwath and Nelson 2016; Rungwattana and Hietz 2018). Thus, trees growing slowly have a greater ability to recover (Bréda et al., 2006; Martin-Benito et al., 2008; Montwé et al., 2015). However, Bottero et al. (2017) showed that the $R_c$ was negatively related to increasing densities in a ponderosa pine stand, which might be related to frequent thinning of their plots, especially for the plot with a low density (the intervals were 5-10 years). Thinning can promote the growth of residual trees, and change their physiological characteristics, which can enhance tree recovery (Thomas et al., 2014; Kiorapostolou et al. 2020), and this physiological response can last up to 15 years for mature ponderosa pines (McDowell et al. 2003).

In contrast, our plots were not thinned after the trees were planted. Thus, our results could avoid the effect of competition mixed with thinning.

Although competition modified tree response to drought, the effect of competition moderately increased tree sensitivity to drought under an intensively competitive environment. Some researchers also showed that the competition effect on restricting trees’ radial growth faded under intensive competition (Gómez-Aparicio et al., 2011; Sánchez-Salgueiro et al., 2015; Dorman et al., 2015; González de Andrés et al., 2017). The calculation of response indices ($R_t$, $R_c$, $R_s$) was based on radial growth.
Thus, the relationship between competition and response indices was also nonlinear. In addition, previous studies showed that the effect of competition decreased with an increase in water stress (Kunstler et al., 2011; Carnwath and Nelson, 2016). In the long term, trees living in high-density stands suffer from more serious drought stress than those living in low-density stands. To adapt to low soil water content they may maintain a lower ratio of leaf area to relative sapwood (Carnwath and Nelson., 2016). This characteristic is conducive to adapting to the increased water stress induced by increased competition.

However, although small-diameter trees also experienced more serious water deficits than large-diameter trees, their response index (Rt and Rs) was more sensitive to the increase in competition. The result has a great relationship with that the growth of small-diameter tree was more sensitive to the change in competition (Gómez-Aparicio et al., 2011). Generally, small-diameter trees commonly live in a less favorable microenvironment (Thomson et al., 1986; Davies et al., 2001). To some extent, the effect of competition was magnified by the difference in the micro-environment. Besides, from low density to high density, the living space of small diameter class decreased more than that of large diameter class (Supplementary Information Fig. S4). Thus, small-diameter trees were more affected by increased competition and their response was more sensitive to the increase in competition.

4.2 Response to interannual climate change

The results also showed that the correlation between growth and interannual climate change was influenced by competition. The competition effect on their response was not constant throughout the whole period. In the early stage competition may have been at a low level. When they were young they had a smaller LAI than when they were mature so the demand for evapotranspiration was lower. And
the water deficit also was not very serious. So the competition effect was not evident. Besides, when they were young trees exhibited high stomatal conductance, photosynthetic rate, and high plasticity (Greenwood et al., 2008; David et al., 2018). Their speeding growth rate might cover the effect of increased competition. However, after 1999, it is obviously that the impact of competition reduced trees’ sensitivity to climate change. This is consistent with previous research indicating that trees living in denser forests were not sensitive to climate change (Ford et al., 2016). In particular, the increase in competition caused trees to become insensitive to wet climate conditions (Carnwath and Nelson 2016). In crowded populations, high evapotranspiration leads to the increased moisture providing fewer benefits to individuals compared with low-density stands (Tamai et al., 2015). In high-density stands, a dense canopy and thick litter intercept some of the precipitation so that the effect of the climate becoming wetter was modulated (Motahari et al., 2013; Gerrits et al., 2010). Therefore, after 1999, although the MSPEI increased, growth at high density was less sensitive than that at low density and showed a relatively low growth rate. Reversely, Kunstler et al. (2011) reported that competition (increased density) had little impact on trees’ climate sensitivity, possibly because changes in other factors moderated the impact of competition.

Compared with large-diameter trees, the small-diameter trees were greatly affected by increased density and were insensitive to interannual climate change. Some researches reported that large-diameter trees were more sensitive to climate (Martín-Benito et al. 2008; Mérian et al., 2011; Guillemot et al., 2015), while other research has shown an opposite result (Jiang et al., 2012). Previous research has demonstrated that large-diameter trees in the upper layer of a stand buffered the effect of climate variation on understory small-diameter trees (Aussenac et al., 2000). However, our experiment was conducted in single-layer stands. The buffer effect might cause little impact on the difference
between diameters. Although it is a single-layer stand, its diameter distribution range is large (Table 1).

In the even-aged stands the differences among small- and large-diameter trees were caused more by competition or other micro-environment differences. The lower sensitivity of small-diameter trees has a close relationship with the loss of plastic capacity induced by intensive competition (Linares et al., 2010). Our results also further demonstrated that small-diameter trees had a lower resilience (lower Rs of small diameter trees in middle- and high-density stands, Fig. 2) than large-diameter trees. In addition, some research showed trees with low growth rates had higher water use efficiency and more rapid stomatal regulation than large trees (Zang et al., 2012; Martínez-Sancho et al., 2017), which helps them to mitigate the effects of drought stress. Therefore, small-diameter trees growth were less sensitive to the climate becoming wetter than that of large trees.

Competition among trees increased and negatively affected trees’ response ability during the process of tree growth. Tree physiology also changes at different ages during this process (David et al., 2018). Besides, in their early stage the demand for water was lower. Thus in high-density stands, the small-diameter trees did not show an obvious increasing trend in a wet period (after 1999). Moreover, as density increased, the slope of the RBAI was obviously decreased. In the future, *P. tabulæformis* in high-density stands will grow slower, and in dry spells, growth may be severely reduced, especially for small-diameter trees.

Overall, trees’ sensitivity to interannual fluctuations in climate was influenced by competition. In this part, the effect of competition on tree responses to climate was not constant and might be associated with the change in trees’ physiological characteristics and other factors, such as worsened soil conditions induced by overcrowded stems (Sun et al., 2018) and demands differing in different
Further study is required to learn more about how tree physiology and competition affect tree
responses to climate. Therefore, in the future, we should be paid more attention to physiological
characteristics in different age classes and the combined effect of physiology and competition.

5 Conclusion

This study investigated the effect of competition on the response of *P. tabulaeformis* to climate.
Competition increased the trees sensitivity to drought. This effect moderately increased under intense
competition. Compared with large diameter trees, the small diameter trees suffering from more
intensive competition were more sensitive to an increase in competition. In contrast, competition
reduced trees’ sensitivity to interannual climate variation. After 1999, the effect greatly affected their
sensitivity, especially in middle- and high-density stands.

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