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

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Abstract As climate changes, understanding tree responses to climate is important to predict tree growth, and plant competition as a nonnegligible biotic factor plays a key role in such responses. 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: 1208 N/ha, 2275 N/ha, 2989 N/ha). The dendroecological method was used to analyze the impact of competition on tree responses to drought and interannual climate variation. The stand density index was used to indicate the intensity of competition. The results showed that competition modified the climate–growth relationship. Competition increased tree sensitivity to drought but the relationship between competition and sensitivity to drought was nonlinear, which suggested that the competition effect slightly increased under intense competition conditions. Additionally, competition reduced trees growth 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 future, these trees presumably may exhibit a reduced sensitivity to interannual climate variation and a greater sensitivity to drought.

Keywords Competition · Drought · Dendroecology · *Pinus tabulaeformis* · Loess Plateau

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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 (Wu et al., 2017). 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 tree resistance to drought or 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 restrict 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 that 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 tree growth responses to climate remains debatable.

Previous studies have shown contrasting results for competition effects on tree responses to drought. Some studies have shown that competition exerts 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 trees mortality in severe drought was not evident in Pinus edulis Engelm. stand. In addition, van Gunst et al. (2016) showed that mortality was reduced in dense forests at mid- and upper-elevation sites.

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 when compared with small-diameter trees. Colangelo et al. (2017) showed that trees that died during 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 increase the risk of hydraulic failure (McDowell et al., 2015). Thus they would be more sensitive to drought than small trees (Lingenfelder and Newbery., 2009; McDowell et al., 2015; Keyser et al., 2016; Zhang et al., 2018).

Additionally, various factors, such as the microenvironment (Holtmeier et al., 2005) and age (Skubel et al., 2015), modulate the competition effect on tree response to drought as the climate warms. All of these factors combined with competition may alter tree responses to drought. For instance, favorable soil conditions can buffer the effect of arid climates (Schoenbeck et al., 2020). Favorable soil conditions can also support more trees, forming high stand density compared with harsh soil conditions (Paoli et al., 2007; Rozendall et al., 2020). The demands of water and nutrient 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 of different ages may vary in response to climate, which may be related to their different physiologies (Greenwood et al., 2008). Some research has reported that the old trees are more sensitive to climate change (Wilson et al., 2004; Wang et al., 2009; Cavin et al., 2017; Gillerot et al. 2021; Jiao et al., 2020), while age is not completely related to tree size. Some old trees with large diameters suffer from low competition pressure. Conversely, some old trees with small sizes suffer from intensive competition. The competition they suffer from at different levels...
(Cescatti et al., 1998) will be combined into the effect of their different physiology to affect tree growth.

As for the competition effect on tree response to interannual climate variation, there are some different views. Some researchers have shown that trees living in an 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 environments displayed divergent growth. Zang et al. (2012) also showed that large trees had closer relationships with climate than that of small trees. However, Jiang et al. (2012) demonstrated that small 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 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 growth response to climate, an experiment was conducted in even-aged Pinus tabulaeformis Carr. plantations that had 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, the initial stand density was too high (approximately 3300 stems/hm²). Previous studies have demonstrated an increased drought vulnerability in dense pine plantations at xeric sites (Sánchez-Salguero 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 purpose of this study was 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.

Materials and methods

Study site

The study site is located in Fangshan County, Luliang city, Shanxi Province, China (111°25’00”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 represented a drought year, 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 with slight differences in soil microenvironmental properties. In April 2019, we investigated the properties of the soil. The physical properties are shown in Table S1 and S2 in the Supplementary Information.

Data collection

To analyze the effect of competition on the response of P. tabulaeformis to climate, 9 impermanent rectangle plots (most plots were 20 × 20 m except for two plots with 10 × 30 m and 10 × 20 m, respectively, when the terrain was not suitable for setting 20 × 20 m) 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 these trees were approximately 29 years old when the experiment was conducted. Although no thinning or self-thinning occurred (when trees got to be matured) in these stands, their densities varied due to different survival rates at beginning We chose nine forest stands and each three representing a stand density gradient. The average low stand density was 1208 stems/hm², the average middle density was 2275 stems/hm², and the average high density was 2989 stems/hm². In the plots,
we measured the diameter at breast height (DBH) of every tree and recorded its coordinates. These trees have a wide range of diameters and they respond differently to climate (Chen et al., 2012). Mérian et al. (2011) also reported that in even-aged stands (generally with a single layer) trees of different sizes showed divergent responses to climate. Thus, we sampled them in two size classes. Due to the diameter range of trees in low-density stands is larger than that in high-density stands, we define different ranges of large-diameter class and small-diameter class in stands with different densities. 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 and larger than 8 cm was defined as the small-diameter class (the DBH of low-density stands [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.

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 the equation as follows:

$$SDI = N(DBH_i/DBH_r)^{1.6}$$

(1)

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, the index diameter of 15 cm or 20 cm was generally chosen. Here, we used 20 cm, which was used by Yan (2009).

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 was 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., Rc > 1 indicates an increase in growth after a drought). Rs is the ability to recover the growth level to that before a drought (here, Rs ≥ 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:

\[ BAI = \pi (r_i^2 - r_{i-1}^2) \]  

\[ Rt = \frac{Dr}{preDr} \]  

\[ Rc = \frac{postDr}{Dr} \]  

\[ Rs = \frac{postDr}{preDr} \]

where \( r \) is the radius of a tree, and \( t \) is the year of a tree ring. \( Dr \), \( preDr \), and \( postDr \) indicate the BAI during drought, and the average BAI of two years before and after a drought, respectively.

To analyze the differences in response indices among trees of different densities and diameters, the

Table 1  Plot information

| Plot | Density (N/ha) | Mean DBH (cm) | DBH range (cm) | Longitude | Latitude | Slope degree | Aspect of slope | Elevation/ m a.s.l | Plot size (m) |
|------|----------------|---------------|----------------|-----------|----------|--------------|-----------------|------------------|---------------|
| 1    | 1125           | 15.5          | 8.2–21.2       | 111°14’42’’ | 37°43’45’’ | 20°          | Shady slope    | 1296             | 20 × 20       |
| 2    | 1375           | 14.34         | 6.9–21         | 111°10’55’’ | 37°47’21’’ | 14°          | Shady slope    | 1461             | 20 × 20       |
| 3    | 1125           | 15.32         | 6.5–22         | 111°10’47’’ | 37°46’52’’ | 15°          | Shady slope    | 1430             | 20 × 20       |
| 4    | 2450           | 12.19         | 5.7–22.1       | 111°14’54’’ | 37°43’24’’ | 15°          | Shady slope    | 1339             | 20 × 20       |
| 5    | 2175           | 11.94         | 5.5–20.5       | 111°14’44’’ | 37°43’27’’ | 24°          | Shady slope    | 1291             | 20 × 20       |
| 6    | 2200           | 13.12         | 4.5–19.1       | 111°14’48’’ | 37°43’27’’ | 22°          | Shady slope    | 1305             | 20 × 20       |
| 7    | 2700           | 11.54         | 5.8–19         | 111°14’53’’ | 37°43’24’’ | 15°          | Shady slope    | 1335             | 20 × 20       |
| 8    | 3267           | 14.50         | 6.1–24.2       | 111°14’48’’ | 37°43’25’’ | 8°           | Shady slope    | 1321             | 10 × 30       |
| 9    | 3000           | 10.84         | 6.3–17.5       | 111°14’52’’ | 37°43’23’’ | 9°           | Shady slope    | 1338             | 10 × 20       |

Fig. 2 Change in (a) temperature, (b) precipitation, and (c) weighted mean of the standardized precipitation evapotranspiration index (MSPEI) at the 8-month scale. The red line is the trend of the variables. The first period was 1989–1999, while the second period was 1999–2017.

Table 1  Plot information

| Plot | Density (N/ha) | Mean DBH (cm) | DBH range (cm) | Longitude | Latitude | Slope degree | Aspect of slope | Elevation/ m a.s.l | Plot size (m) |
|------|----------------|---------------|----------------|-----------|----------|--------------|-----------------|------------------|---------------|
| 1    | 1125           | 15.5          | 8.2–21.2       | 111°14’42’’ | 37°43’45’’ | 20°          | Shady slope    | 1296             | 20 × 20       |
| 2    | 1375           | 14.34         | 6.9–21         | 111°10’55’’ | 37°47’21’’ | 14°          | Shady slope    | 1461             | 20 × 20       |
| 3    | 1125           | 15.32         | 6.5–22         | 111°10’47’’ | 37°46’52’’ | 15°          | Shady slope    | 1430             | 20 × 20       |
| 4    | 2450           | 12.19         | 5.7–22.1       | 111°14’54’’ | 37°43’24’’ | 15°          | Shady slope    | 1339             | 20 × 20       |
| 5    | 2175           | 11.94         | 5.5–20.5       | 111°14’44’’ | 37°43’27’’ | 24°          | Shady slope    | 1291             | 20 × 20       |
| 6    | 2200           | 13.12         | 4.5–19.1       | 111°14’48’’ | 37°43’27’’ | 22°          | Shady slope    | 1305             | 20 × 20       |
| 7    | 2700           | 11.54         | 5.8–19         | 111°14’53’’ | 37°43’24’’ | 15°          | Shady slope    | 1335             | 20 × 20       |
| 8    | 3267           | 14.50         | 6.1–24.2       | 111°14’48’’ | 37°43’25’’ | 8°           | Shady slope    | 1321             | 10 × 30       |
| 9    | 3000           | 10.84         | 6.3–17.5       | 111°14’52’’ | 37°43’23’’ | 9°           | Shady slope    | 1338             | 10 × 20       |
Mann–Whitney–Wilcoxon test was used (Hollander et al., 1973). Additionally, the dated series was 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 (modified negative exponential curve) was used to remove tree growth trends (Bunn et al., 2020). The detrended series was then used to calculate TRWI by using the bi-weight robust mean (Cook and Kairiukstis 1990). In addition, the residual chronology (RTRWI), which was established by an omission autoregression component. This process was conducted by using the R package “dplR” (Bunn et al., 2020).

Climate data

Monthly climate data (i.e., precipitation and temperature) from 1989 to 2016 for the Lishi area which is 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 standardized precipitation evapotranspiration index (SPEI, Beguería et al., 2017). 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). To determine the average conditions of a year, we selected the 8-month SPEI (SPEI8), to calculate the mean standardized precipitation evapotranspiration index (MSPEI). Due to the climate condition in each month causing different effect on tree growth, we considered the weighted average method (Wang et al., 2017) to calculate the average effect of SPEI. We regarded the weight of the correlation coefficient between SPEI8 and RTRWI as the weighting factor.

\[
MSPEI = \frac{\sum_{i=1}^{12} \sum_{j=1}^{12} \alpha_i C_j}{\sum_{i=1}^{12} \alpha_i}
\]

where \(\alpha_i\) is the correlation coefficient between SPEI and TRWI at an 8-month scale. The \(C_j\) is the value of SPEI at an 8-month scale.

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 of R) using the “nlme” package in R (Pinheiro et al., 2019). 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 the plot effect versus those considering the effects of both the plot and the individual (Pinheiro et al., 2000). The model was expressed as follows:

\[
R = \alpha SDI + \beta + \epsilon
\]

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

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 end, the length of the correlation series equal to the moving window will be lost). 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 (relative basal area increment, RBAI, was calculated using the ratio of the BAI to the MSPEI) in each density and diameter to analyze the change in tree response to climate in the long term.

The RBAI is similar to that 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 Eq. 7. The larger the \(\alpha\), the more sensitive the tree is to climate conditions. The
ratio (α, 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 (Eq. 9).

\[ BAI = \alpha \cdot MSPEI \]  
\[ \alpha = \frac{BAI}{MSPEI} \]  

where \( \alpha \) is the coefficient.

However, the volatility of RBAI is very large, which leads to an insignificant trend. The moving average is a method that has been widely used to reduce fluctuations in 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 index (STRWI, which has a closer relationship with climate than residual chronology, Supplementary Information Table S5 and Table S6) and SPEI8.

Results

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 Rc was positively related to the increase in density. Among densities, the differences in 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).

Competition effect on tree 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 Rt to decrease, and Rc to increase in the whole series (Table 2). The form of the model (including \(Rt^{0.5}\) and \(Rc^{-0.25}\)) also showed that the relationships between SDI and Rt or Rc were not linear (Fig.S1 and Fig.S3 also showed the nonlinear relationship between competition, and Rt and Rc). It suggested that the rate of Rt decline and the rate of increase in Rc decreased with increasing SDI. Thus, in the dense stand, the sensitivity of the response index to the variation in competition declined. Additionally, the Rs 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 Rt and Rs 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.

### Tree growth response to inter-annal climate variation

Tree growth at different densities varied significantly. Before 1999, the BAI increased, while after 1999, it increased slowly. In high-density stands, the change was more obvious than that in low-density stands (Fig. 4). The BAI of small-diameter trees changed more significantly than that of large ones. It means that competition restrained tree growth in the long term.

As Fig. 5 shows that tree 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. In middle- and high-density stands the correlations were higher in large trees than that in small ones.

In long term, the change in MRBAI varied significantly. Before 1999, MRBAI increased, and large-diameter trees showed a faster increase than small trees. While after 1999, the trend of MRBAI got flat and even in high-density stands, the MRBAI declined. It means that as trees grew, the increasing competition intensity caused a decline in their sensitivity of response to the favorable climate conditions (after 1999 SPEI increased, Fig. 2).

### Discussion

#### Competition effect on tree response 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 deficit. We found a negative relationship between the SDI and Rt, which was consistent with results of

| Table 2 | Summary of the results of the linear mixed effect models for the competition effect on tree response to drought. The whole series refers to all series combined for the analysis |
|---|---|---|---|---|
| Variables | Intercept | SDI | Marginal \(R^2\) | Conditional \(R^2\) |
| Whole series | \(Rt^{0.5}\) | 1.0008 | –0.0003 | 0.1127 | 0.5498 |
| | \(Rc^{-0.25}\) | 1.1019 | –0.0002 | 0.1281 | 0.3629 |
| | \(Rs^{0.5}\) | 0.9200 | –0.0001 | 0.0054 | 0.1661 |
| L1 | \(Rt^{0.5}\) | 1.0055 | –0.0003 | 0.1145 | 0.6054 |
| | \(Rc^{-0.5}\) | 1.0968 | –0.0003 | 0.1185 | 0.2525 |
| | \(Rs\) | 0.9007 | –0.0001 | 0.0061 | 0.2414 |
| L2 | \(Rt^{0.5}\) | 1.0604 | –0.0004 | 0.1571 | 0.5553 |
| | \(Rc^{0.25}\) | 0.8426 | 0.0003 | 0.1151 | 0.4272 |
| | \(Rs\) | 0.9727 | –0.0002 | 0.0301 | 0.2201 |

\(L1\): indicates the large-diameter class. \(L2\): represents the small-diameter class

The bold type means that the estimation is significant.
Gyenge et al. (2012) and Gleason et al. (2017). In addition, in our experiment, the effect of 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, varied microenvironment, and their characteristics. Under a weak competition environment, the effect of competition was easily be covered by the influence of other factors, especially for the varied microenvironment. The favorable microenvironment could moderate water stress and competition (Rozen dall et al., 2020). Additionally, the individual differences may also weaken the effect of competition on tree responses to drought. Previous research has shown that individual differences played a critical role in tree responses to climate (Trouillier et al., 2018). Thus, the difference of microenvironment and individuals might moderate the pressure of competing for resources in a dry spell and weakened the relationship between Rt and SDI.

In general, the Rc is negatively related to the Rt (Gazol et al., 2017) but positively to increasing competition. The previous research has shown that increased competition leads to a decrease in radial growth (Hui et al., 2018), but the trees have high proportions of latewood with relatively thicker cell walls. And these trees also have low wood density and high hydraulic conductivity, which indicates a low susceptibility of subjecting to hydraulic failure (Carnwath and Nelson, 2016; Rungwattana and Hietz, 2018). Thus, trees growing slowly have a greater ability to recover (Brêda et al., 2006; Martin-Benito et al., 2008; Montwé et al., 2015). However, Bottero et al. (2017) showed that the Rc 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 the remaining trees, and change their physiological characteristics, thus enhancing their 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. The differences in the stand densities were mainly related to the different survival rate at beginning rather than recent years. When we investigated in 2018, in high-density stands, several trees died (the canopies were still not close; there were less than five mature trees that died; supplementary information Fig.S5), while there were no mature trees that died in low-density stands. It might be relate to at the beginning the condition in high-density stand was better than that of low- and middle-density stands (the average slope degree of high-density stands was flatter, which was conducive to the infiltration of rain water and supported of more trees. While large number of trees changed soil condition (Qiu et al., 2019) and caused more intensive competition in high-density stands). Thus, our results could avoid the effect of competition mixed with thinning.

Additionally, our results indicated that the Rt of large trees were greater than that of small trees. This is associated with large trees developing a wider range of
roots and larger crowns that could help them to compete for more resources than smaller trees to resist drought (Burt et al., 1985). In addition, their large stems could store more water for drought resistance (Phillips et al., 2003; Zang et al., 2014). All of these reasons are more conducive to large trees resisting drought. However, some studies have shown that large trees suffered from a greater impact and were subjected to drought-induced mortality (Martínez-Vilalta et al., 2012; Bennett et al. 2015; Shenkin et al. 2018). Large trees have longer hydraulic path lengths and higher hydraulic resistance (Domec et al., 2008), which makes them more vulnerable to hydraulic failure (Ryan et al., 2006). Besides, in their studies, the ages might differ between large- and small-diameter trees. In some cases, larger trees are older than smaller ones. 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 difference might derive from both uneven 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 mostly stems from the different growth rates and competition intensity. Finally, in Martínez-Vilalta’s et al. (2012), the species, Scots pine, is sensitive to high temperature. In contrast, P. tabulæformis can tolerate drought and high temperature (Zeng et al., 2005). Therefore, differences in species characteristics and forest structure may also lead to differences in tree resistance to drought.

On the whole, competition modified tree response to drought, but the effect of competition moderately increased tree sensitivity to drought in an intensively competitive environment. On the one hand, the process of tree growth response to increased competition was nonlinear. Some researchers 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 (Rt, Rc, Rs) was based on radial growth. Thus, the relationship between competition and response indices was also nonlinear. On the other hand, 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. Previous studies also showed that the effect of competition decreased with an increase in water stress (Kunstler et al., 2011; Carnwath and Nelson, 2016).

However, although small-diameter trees also experienced more serious water deficits than large-diameter trees, their response indices (Rt and Rs) was more sensitive to the increase in competition. This result has a strong relationship with the fact that the growth of small-diameter trees is more sensitive to changes in competition (Gómez-Aparicio et al., 2011). Generally, at the beginning of planting, they were similar to others, and some saplings died soon, which caused uneven resources distribution (Supplementary Information Fig. S4). Besides, soil and topography also vary in plots. Favorable microenvironment was more conducive to a high net photosynthetic rate and the formation of large trees (Woo et al., 2005). Small-diameter trees commonly live in a less favorable microenvironment (Thomson et al., 1986; Davies et al., 2001). Then differences in the microenvironment would enhance the divergent growth rate and tree size (Zhang et al., 2017). To some extent, the effect of competition was magnified by the difference in the microenvironment. Besides, from low density to high density, the living space of the small-diameter class decreased more than that of the 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. See Fig. 6

Tree growth 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. Young plants had a smaller leaf area index than mature trees so the demand for evapotranspiration was lower. In addition, the water deficit was also not very serious. Thus, the competition effect was not evident. Besides, young trees exhibited high stomatal conductance, photosynthetic rate, and
plasticity (Greenwood et al., 2008; David et al., 2018). Their speeding growth rate might cover the effect of increased competition. However, after 1999, it was obvious that the impact of competition reduced trees’ sensitivity to wetter climates. This is consistent with previous research indicating that trees living in denser forests were not sensitive to wet climate conditions (Carnwath and Nelson, 2016; Ford et al., 2016). Possible explanations are that 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 (Gerrits et al., 2010; Carlyle-Moses and Gash, 2011). 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. Conversely, Kunstler et al. (2011) reported that competition (increased density) had little impact on tree growth sensitivity to climate, 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 less sensitive to interannual climate change. Some researchers also reported that large trees were more sensitive to climate (Martín-Benito et al. 2008; Mérian et al., 2011; Guillenot et al., 2015), while other research has shown the opposite result (Jiang et al., 2012). Previous research has demonstrated that large trees in the upper layer of a stand buffered the effect of climate variation on understory small trees (Aussenac et al., 2000). However, our experiment was conducted in single-layer stands. The buffer effect might have little impact on the difference between diameters. The lower sensitivity of small-diameter trees might be closely related to 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. Lower resilience may cause them to show longer and more severe legacy effect, likely resulting in less sensitivity to climate in subsequent growth (Camarero et al., 2018). In addition, some research has shown that trees with low growth rates have 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 tree growth

![Fig. 6 Change in the MRBAI at different densities and diameters. The first period was 1990–1999. The second period was 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.](image-url)
was less sensitive to the climate becoming wetter than that of large 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 tree physiological characteristics and other factors, such as worsened soil conditions induced by overcrowded stems (Sun et al., 2018) and demands differing in different stages. Further study is required to learn more about how tree physiology and competition affect tree response to climate. Therefore, in future, we should pay more attention to physiological characteristics in different age classes and the combined effect of physiology and competition.

Conclusion

This study investigated the effect of competition on the response of *P. tabulaeformis* to climate. Competition increased tree 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 tree growth sensitivity to interannual climate variation. After 1999, the effect greatly affected tree sensitivity to climate getting wetter, especially in middle- and high-density stands.

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Authors’ contributions Rumeng He collected the data and wrote most of the article. Xuhu Wang developed the idea and modified the article. Tao Liu drew Fig. 1, modified the article, and polished the language. Lijun Guo helped to collect and calculate the data. Alamgir Khan modified and edited the manuscript.

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Data Availability The data are provided in the Supplementary Material.

Code availability Not applicable.

Declarations

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