

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

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## Research Article

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1 **Title page**

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

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18 **Abstract:** With climate change, understanding tree responses to climate is important for predicting

19 trees' growth, and plant competition as a nonnegligible biotic factor plays a key role in such response.

20 However, few studies have investigated how competition affects the response of *Pinus tabulaeformis*

21 plantations to climate . In our study, we investigated nine 29-year-old *P. tabulaeformis* plantation plots  
22 (three density gradients). The dendroecological method was used to analyze the impact of competition  
23 on trees response to drought and interannual climate variation. Stand density index was used to indicate  
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25 relationship. Competition increased trees' sensitivity to drought but the relationship between  
26 competition and sensitivity to drought was nonlinear. The competition effect slightly increased under  
27 intense competition conditions. Additionally, competition reduced trees' sensitivity to interannual  
28 climate variation. After 1999, the effect of competition was obvious. The sensitivity of small-diameter  
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30 presumably may exhibit a reduced sensitivity to interannual climate variation and a greater sensitivity  
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41 **Authors' contributions:** Rumeng He collected the data and wrote most part of the article. Xuhu Wang  
42 developed the idea and modified the article. Tao Liu drew Fig.1 and modified the article, and polished  
43 the language. Lijun Guo helped to collect and calculate the data. Baitian Wang wrote the abstract of the  
44 article. Alamgir Khan modified and edited manuscript.

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59 Impact of intraspecific competition on the growth of *Pinus tabulaeformis*  
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76 **1 Introduction**

77 With climate warming, the frequency of drought is increasing, which has a great effect on  
78 ecosystems. Forests are vegetation types that are highly affected by drought. The response of forests to

79 drought is influenced by many factors such as damage by insects (DeLucia et al. 2012), nitrogen  
80 deposition (Hannusch et al., 2019), an increase in carbon dioxide concentration, and competition. The  
81 attack of insects may reduce trees resistance to drought or may increase the rate of tree mortality  
82 (Stephenson et al., 2019). A higher carbon dioxide concentration can increase water use efficiency, thus  
83 moderating water stress (Rahman et al., 2019). Competition is also a critical factor influencing tree  
84 growth and response to climate. Intense competition may exacerbate resource shortages. In a  
85 high-competition environment, serious water stress in drought years will affect the physiological  
86 activities of trees (Laurent et al. 2003; McDowell et al., 2011; Archambeau et al. 2020; Schmitt et al.  
87 2020), cause growth decline (Jump et al., 2006), forest dieback (Rubio-Cuadrado et al., 2018; Gessler  
88 et al., 2018; Zhao et al., 2018), and even reduce biodiversity (Peng et al., 2011; Ploughe et al., 2019).  
89 On the Loess Plateau of China, due to the high stand density there are large areas of dense plantations  
90 which are suffering from intense competition. Furthermore, the region might become more arid as the  
91 climate warms (Liu et al., 2018), which can further exacerbate plant competition, substantially  
92 influencing the sustainability of the local ecosystem. Therefore, understanding the competition effect  
93 on the response of the major species to climate is essential for forest management. However, how  
94 competition affects trees' response to climate remains debatable.

95 Previous studies have shown contrasting results for competition effects on tree responses to drought.  
96 Some researches showed that competition increases with increasing stand density, which may exert a  
97 considerable impact on the performance of trees during arid spells. For example, Gleason et al. (2017)  
98 observed that competition exaggerated the water deficit and reduced tree resistance during a drought  
99 event. Similarly, Bottero et al. (2017) found that competition caused a growth decline in ponderosa  
100 pine and led to its low resilience. In addition, Zhang et al. (2015) concluded that intensive competition

101 may increase the mortality rate of trees with a weak ability to compete for resources. In contrast, Floyd  
102 et al. (2009) showed that the effect of competition on tree mortality in severe drought was not evident  
103 in *Pinus edulis* Engelm. stand. In addition, van Gunst et al. (2016) showed that in mid- to  
104 upper-elevation forests, mortality reduced in dense forests.

105 Competition also differs among trees of different sizes, which causes divergent responses to drought.  
106 Dominant trees with large diameters have stronger competitive abilities to obtain soil water and  
107 nutrients. These trees have a greater potential to tolerate water stress and are less sensitive to arid  
108 climates compared with small-diameter trees. Colangelo et al. (2017) showed that trees which died in  
109 drought are smaller than living trees. However, in some cases, large trees demand more water. They  
110 receive more solar radiation and have longer hydrologic paths than small trees, which could increase  
111 the risk of hydraulic failure (McDowell et al., 2015). Thus they would be more sensitive to drought  
112 than small-diameter trees (Lingenfelder and Newbery., 2009; McDowell et al., 2015; Keyser et al.,  
113 2016; Zhang et al., 2018).

114 Additionally, various factors, such as micro-environment (Holtmeier et al., 2005), and age (Skubel et  
115 al., 2015), modulate the competition effect on trees' response to drought as the climate warms. All of  
116 these factors combining with competition may alter trees responses to drought. For instance, favorable  
117 soil conditions can buffer the effect of arid climates (Schönbeck et al., 2020). Favorable soil conditions  
118 can also support more trees, forming high stand density compared with harsh soil conditions (Paoli et  
119 al., 2007). Water and nutrient demands increase as the stand grows, forming an intense competition  
120 environment. Dense forests also consume more nutrients and deteriorate soil conditions, leading to  
121 more intense competition (Qiu et al., 2019). This process leads to the effects of competition mixed with

122 soil conditions. Besides, the growth of trees with different ages may vary in response to climate  
123 (Wilson et al., 2004; Wang et al., 2009; Cavin et al., 2017; Gillerot et al. 2020; Jiao et al., 2020), which  
124 may be related to their different physiologies (Greenwood et al., 2008) and the competition they suffer  
125 from at different levels (Cescatti et al., 1998). These two factors would be mixed when analyzing the  
126 competition effect on the response of trees of different sizes.

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

139 To deeply understand the effects of competition on tree responses to climate, an experiment was  
140 conducted in even-aged *Pinus tabulaeformis* Carr. plantations that have not been thinned after they  
141 were planted. *P. tabulaeformis* is one of the major planting species in northern China. This species has  
142 been widely planted on the Loess Plateau to prevent soil erosion due to its properties, such as drought

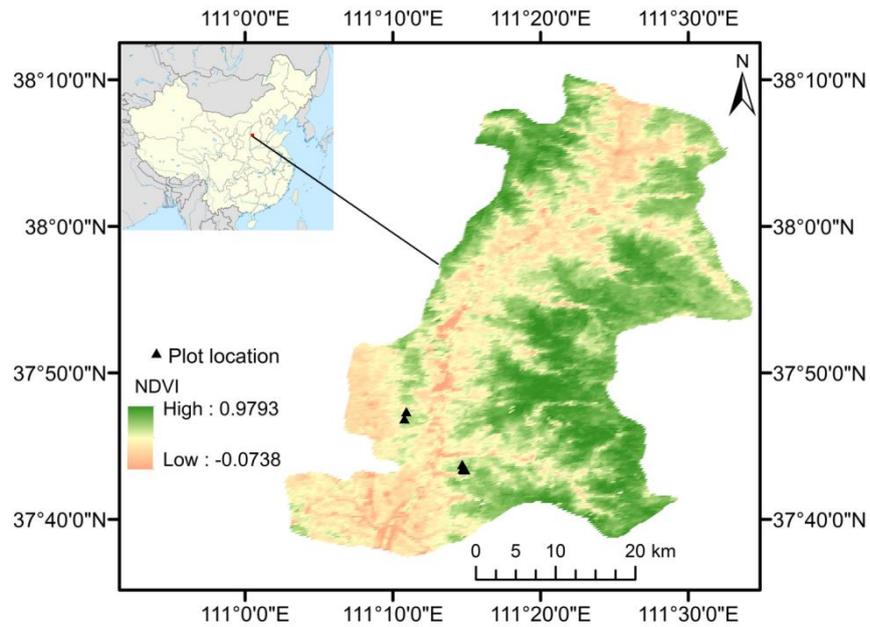
143 resistance and tolerance to barren soil (Zhou et al., 2007). However, because of the high stand density  
144 (initial stand density of 3300 stems/hm<sup>2</sup>), the trees' radial growth was slow, and some individuals are  
145 growth decline (Berger et al., 2004). Previous studies have demonstrated an increased drought  
146 vulnerability in dense pine plantations at xeric sites (Sánchez-Salguero et al., 2013). Thus, climate  
147 warming may also increase risks to these individuals and considerably impact their ecological functions.  
148 However, few studies have explored the impacts of competition on the response of *P. tabulaeformis*  
149 plantations to climate in the local areas. The main purposes of this study were to explore how  
150 competition affects the response of *P. tabulaeformis* to drought, and interannual climate variation. We  
151 hypothesized that: 1) competition increases the sensitivity of *P. tabulaeformis* to drought, and the effect  
152 may markedly increase with an increase in competition and that 2) the species sensitivity in response to  
153 interannual climate variation may gradually decrease due to increasing competition.

## 154 **2 Materials and methods**

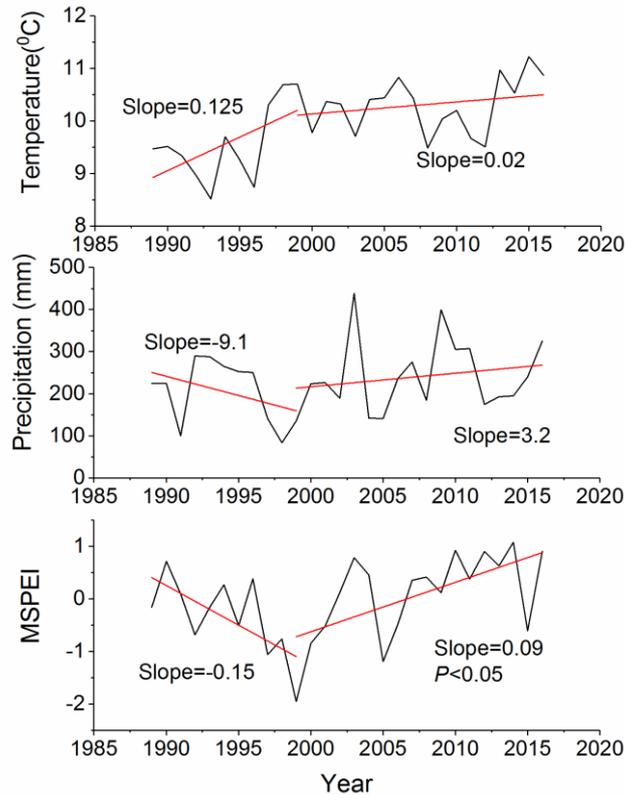
### 155 **2.1 Study site**

156 The study site is located in Fangshan County, Luliang city, Shanxi Province, China  
157 (111°2'50"E-111°34'30"E, 37°36'58"N-38°18'27"N, Fig. 1). This area has a temperate continental  
158 climate. The average annual temperature is 7.3 °C, and the mean annual precipitation ranges from 440  
159 to 650 mm ([http://www.fangshan.gov.cn/zjfs/zrdl/201807/t20180709\\_732551.html](http://www.fangshan.gov.cn/zjfs/zrdl/201807/t20180709_732551.html)). Higher  
160 precipitation often occurs in summer. Drought events have frequently occurred, especially in 1992,  
161 1997, 1999-2000, 2005-2006, and 2015 (these years with mean standardized precipitation  
162 evapotranspiration index (MSPEI) values less than -0.5 representing a drought years, Fig. 2, Yu et al.,  
163 2014). In the 1990s, the dry period substantially affected the local forest ecosystem

164 .The predominant soil type of local area is loess. Generally, the depth of soil is deep. Due to the  
165 differences in microenvironment, there are slight differences in soil properties in local areas. In Apr.  
166 2019, we investigated the properties of the soil. The physical properties of the soil are shown in Table  
167 S1 and Table S2 in the Supplementary Information.



168  
169 **Fig. 1** Location of the study site. The background of the main map is the normalized difference  
170 vegetation index (NDVI) in 2015. The NDVI data derived from MOD13Q1 was downloaded from the  
171 National Oceanic and Atmospheric Administration (NOAA)



172

173 **Fig. 2** Change in MSPEI. MSPEI is the weighted average of the standardized precipitation  
 174 evapotranspiration index (SPEI) at the 8-month scale.

175 **2.2 Data collection**

176 To analyze the effect of competition on the response of *P. tabulaeformis* to climate, 9 impermanent  
 177 rectangle plots with similar elevations and aspects were set in even-aged pure *P. tabulaeformis*  
 178 plantations in May 2018 (Table 1). All of these monoculture plantations were planted in the 1980s and  
 179 were not thinned after being planted. These trees were approximately 29 years old when the experiment  
 180 was conducted. We established three density gradients. In each density gradient, the plots were set in  
 181 three stands with similar density (total of 9 densities). The average low stand density was 1208  
 182 stems/hm<sup>2</sup>; the average middle density was 2275 stems/hm<sup>2</sup>; and the average high density was 2989  
 183 stems/hm<sup>2</sup>. In the plots, we measured the diameter at breast height (DBH) of every tree and recorded its  
 184 coordinate. Since the diameter range was relatively large and, generally, trees of different sizes in a

185 stand responded differently to climate (Chen et al., 2012). Mérian et al.(2011) also showed that in even  
 186 aged stand (generally even-aged stand with single layer) it is divergent that trees of different size  
 187 responses to climate. Thus, we sampled them in two size classes. Because the tree sizes of the  
 188 low-density stands were larger than those of the high-density forest, the diameter was classified  
 189 according to 65% of the maximum DBH. A DBH greater than 65% of the maximum DBH of the  
 190 density was defined as the large-diameter class (the DBH range of low-density stands [14.3, 22] cm, of  
 191 middle-density stands [13.8, 21.3] cm, and of high-density stands [12.2, 18.8] cm). In contrast, a DBH  
 192 less than 65% of the maximum DBH but larger than 6 cm was defined as the small-diameter class (the  
 193 DBH of low-density stands ranged [8, 14.2] cm, of middle-density stands [8,13.7] cm, and of  
 194 high-density stands [8, 12.1] cm). Two cores per tree were taken from at least 7 trees of every diameter  
 195 class in each plot. Each core was drilled at breast height, and the direction was parallel to the contour  
 196 line of the hillside. In total, we obtained 260 cores.

197

**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

8	3267	14.50	6.1-24.2	111°14'48"	37°43'25"	8°	N3°	1321	10×30 m
9	3000	10.84	6.3-17.5	111°14'52"	37°43'23"	9°	N257°	1338	10×20 m

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### 198 2.3 Calculation of the competition index

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

$$202 \quad SDI = N(DBH_i / DBH_r)^{1.6} \quad (1)$$

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

### 207 2.4 Calculation of response indices and the tree ring width index

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

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

216 drought compared with that in an arid year (i.e.,  $R_c > 1$  indicates an increase in growth after a drought).  
217  $R_s$  is the ability to recover the growth level to that before a drought (here,  $R_s = 1$  indicates complete  
218 recovery to predrought growth; otherwise the tree is still experiencing a legacy effect of the drought;  
219 Martínez-Vilalta et al., 2012; George et al., 2015). In this case, we studied the drought year 2015. Two  
220 years before and after the drought year were taken as background years for comparison. The equations  
221 are as follows:

$$222 \quad BAI = \pi(r_t^2 - r_{t-1}^2) \quad (2)$$

$$223 \quad R_t = Dr / preDr \quad (3)$$

$$224 \quad R_c = BAI_{post} / Dr \quad (4)$$

$$225 \quad R_s = postDr / preDr \quad (5)$$

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

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

230 Additionally, the dated series were also used to calculate the tree ring width index chronology  
231 (TRWI) of the whole series and of different densities and diameter classes. To develop the standardized  
232 tree-ring width chronology (STRWI), the “ModNegExp” method was used to remove tree growth  
233 trends. The detrended series was then used to calculate TRWI by using beweight robust mean. In

234 addition, the residual chronology (RTRWI) was also established. This process was conducted by using  
235 the R package “dplr” (Bunn et al., 2020).

## 236 **2.5 Climate data**

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

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

## 249 **2.6 Analysis of trees responding to climate**

250 To evaluate the effect of competition on trees’ response to drought, we developed a linear  
251 mixed-effect model for response indices (values were converted to a normal distribution by the square  
252 root, high th-root transformations, and reciprocal. The best method was selected by using  
253 “powerTransform” function in the “car” package ) using the “nlme” package in R (Pinheiro et al.,

254 2019). The random effect only considered the plot effect due to the superior results of the residual plot  
255 and qq plot of the model considering only plot effect versus those considering the effects of both the  
256 plot and the individual (Pineiro et al., 2000). The model was expressed as follows:

$$257 \quad R = \alpha SDI + \beta + \varepsilon \quad (6)$$

258 where R is the response index (R<sub>t</sub>, R<sub>c</sub>, R<sub>s</sub>); SDI is a fixed effect,  $\beta$  is a random effect derived from the  
259 plot;  $\alpha$  and  $\varepsilon$  are the coefficient and error, respectively. All statistical analyses were conducted using R  
260 3.5.1 (R Core Team 2018).

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

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

274  $BAI = \alpha \bullet MSPEI$  (6)

275  $\alpha = BAI / MSPEI$  (7)

276 where  $\alpha$  is the coefficient.

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

## 284 **3 Results**

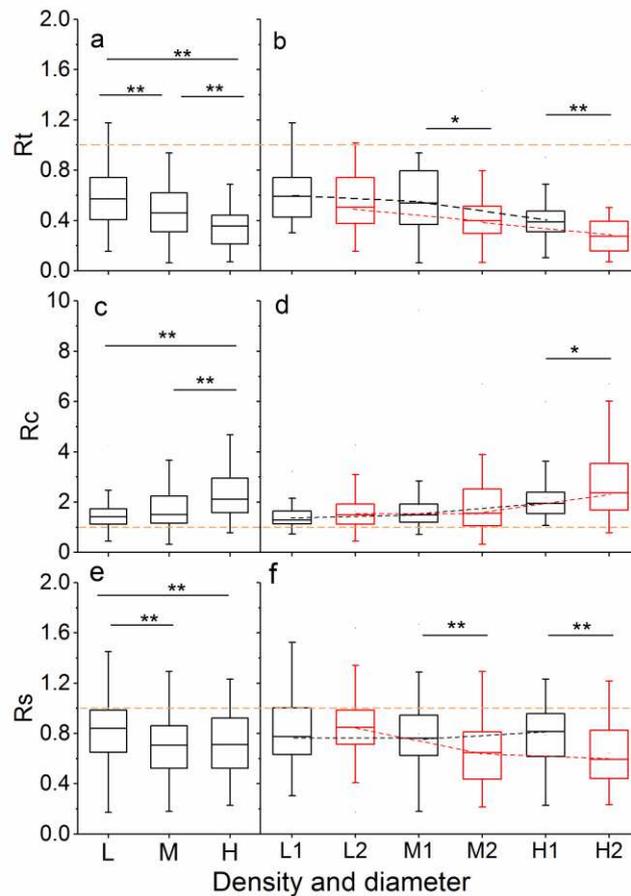
### 285 **3.1 Tree growth response to drought**

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

292 In contrast, the change in the  $R_c$  was positively related to the increase in density. Among densities,  
293 the differences in the  $R_c$  were significant (middle-high density  $W=6114$ ,  $P<0.01$ ; low-high density

294  $W=1629, P<0.01$ , Fig. 3c). Between diameters, the  $R_c$  of the small-diameter trees was larger than that  
 295 of the large-diameter trees, and the difference was significant at the high density ( $W=1156, P<0.01$ , Fig.  
 296 3d), showing that the  $R_c$  of the small-diameter trees was more sensitive to the density increase than that  
 297 of large-diameter trees.

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



302

303 **Fig. 3** Response indices among different densities and diameters. The letters L, M, and H  
 304 represent low-, middle-, and high-density stands, respectively. The numbers 1 and 2 represent  
 305 large- and small-diameter trees, respectively. Two asterisks indicate significant differences

306 between diameters or densities ( $P<0.01$ ), \*, significant at  $P<0.05$ ; \*\*, significant at  $P<0.01$ . The  
307 orange dash line is the value equal to one.

### 308 **3.2 Competition effect on trees' response to drought**

309 As density increased, the competition increased, which heightened tree sensitivity in response to  
310 drought. The results of the linear mixed models showed that the significant effect of increased SDI  
311 caused the  $R_t$  to decrease, and  $R_c$  to increase in the whole series (Table 2). The form of the model  
312 (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  
313 linear (Fig.S1 and Fig.S3 also showed the nonlinear relationship between competition, and  $R_t$  and  $R_c$ ).  
314 It suggested that the rate of  $R_t$  decline and the rate of increase in  $R_c$  reduced with the increase of SDI.  
315 Thus, in dense stand trees resistance to drought and recovery from drought were not sensitive to the  
316 change in competition. The  $R_s$  also decreased as the competition increased, but this relationship was  
317 not significant.

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

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

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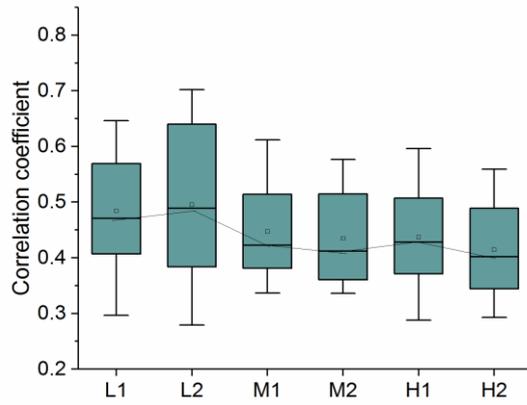
Variables	Intercept	SDI	Marginal $R^2$	Conditional $R^2$
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	Rt <sup>0.5</sup>	<b>1.0008</b>	-0.0003	0.1127	0.5498
Whole series	Rc <sup>-0.25</sup>	<b>1.1019</b>	<b>-0.0002</b>	0.1281	0.3629
	Rs <sup>0.5</sup>	<b>0.9200</b>	-0.0001	0.0054	0.1661
	Rt <sup>0.5</sup>	<b>1.0055</b>	-0.0003	0.1145	0.6054
Lc	Rc <sup>-0.5</sup>	<b>1.0968</b>	<b>-0.0003</b>	0.1185	0.2525
	Rs	<b>0.9007</b>	-0.0001	0.0061	0.2414
	Rt <sup>0.5</sup>	<b>1.0604</b>	-0.0004	0.1571	0.5553
Sc	Rc <sup>0.25</sup>	<b>0.8426</b>	0.0003	0.1151	0.4272
	Rs	<b>0.9727</b>	-0.0002	0.0301	0.2201

### 327 3.3 Growth response to inter-annual climate variation

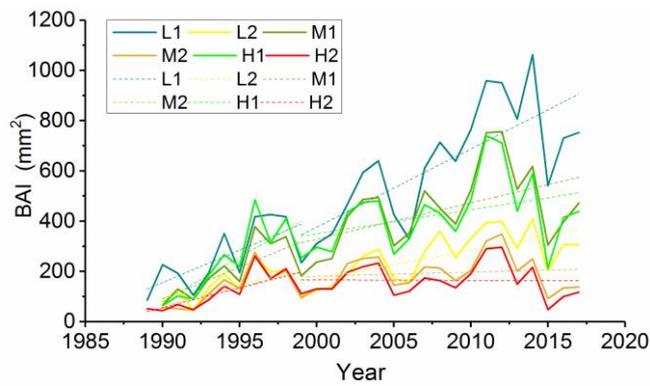
328 Trees' sensitivity to interannual climate variation was weakened by increased competition. The  
329 average correlation value between SPEI8 and STRWI was higher in the low-density stand than in the  
330 high-density stand (Fig.4). Before 1999, MSPEI declined (Fig.2), while BAI showed upward trends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



335

336

**Fig. 4** Average correlation between STRWI and SPEI8 from low density. to high density.



337

338

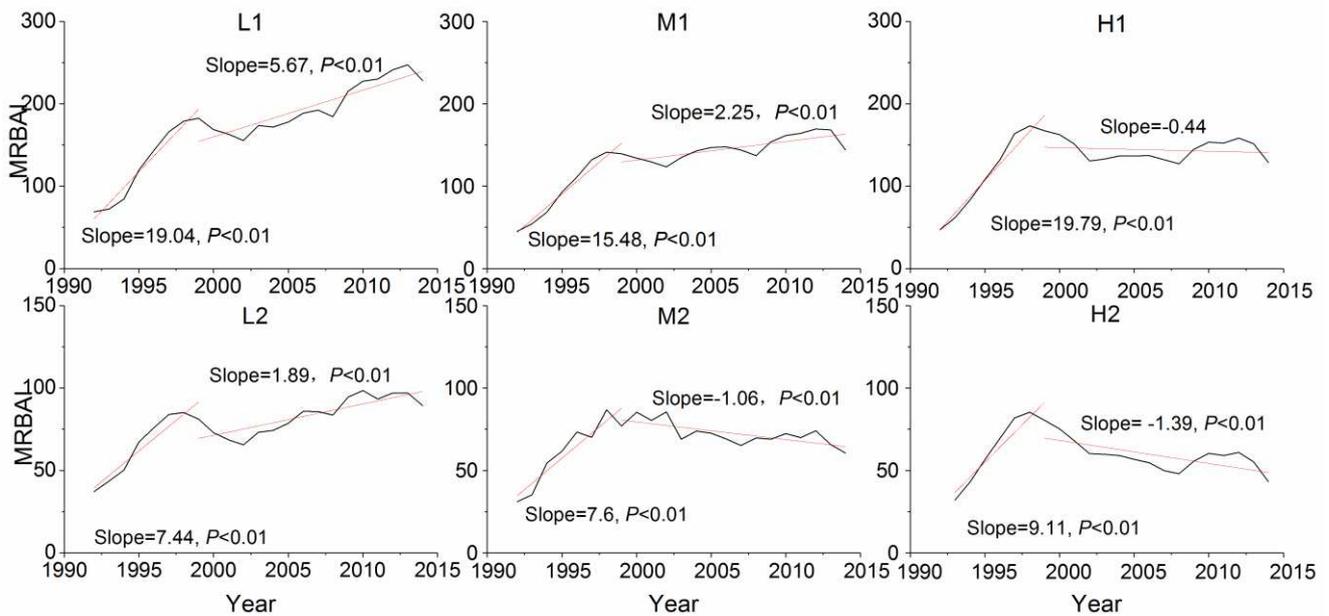
**Fig. 5** Development of BAI. The basal area increment (BAI) is the average of each plot and diameter.

339

The letters L, M, and H represent low-, middle-, and high-density stands, respectively. The numbers 1

340

and 2 represent large diameters and small diameters, respectively.



341

342

**Fig. 6** Change in the MRBAI at different densities and diameters. The first period is 1990-1999. The

343 second period is 1999-2017. The letters L, M, and H represent low-, middle-, and high-density stands,  
344 respectively. The numbers 1 and 2 represent large diameters and small diameters, respectively.

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

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

## 360 **4 Discussion**

### 361 **4.1 Competition effect on tree responses to drought**

362 Competition exerts impacts on tree responses to drought. Our results also showed that competition  
363 significantly increased tree sensitivity to drought. With an increase in stand density, the competition for

364 water and nutrients became more intense (Vernon et al., 2018). Generally, increased competition  
365 worsens water resource shortages. We found a negative relationship between the SDI and  $R_t$ , which is  
366 consistent with the results of Gyenge et al. (2012) and Gleason et al. (2017). In addition, in our  
367 experiment, the effect of the SDI on the  $R_t$  was very weak for large-diameter trees, while the random  
368 effect had a considerable impact, which was mainly related to the weak competition from their  
369 neighbors and more favorable microenvironment. Large trees occupy a larger living space benefitting  
370 to developing their wider range of roots and larger crowns that could obtain more resources than  
371 smaller ones (Burt et al., 1985; Supplementary Information Fig. S4). In addition, their large stems  
372 could store more water for drought resistance (Phillips et al., 2003; Zang et al., 2014). Thus, they were  
373 less affected by competition.

374 However, some studies showed that large trees suffered greater impact and subjected to  
375 drought-induced mortality (Martínez-Vilalta et al., 2012; Bennett et al. 2015; Shenkin et al. 2018).  
376 Large trees had longer hydraulic path length and higher hydraulic resistance (Domec et al., 2008),  
377 which made them more vulnerable to hydraulic failure (Ryan et al., 2006). Besides, in their researches,  
378 the ages might differ between large- and small-diameter trees. In some cases, larger trees that suffer  
379 from weak competition are older than smaller ones that suffer from intense competition. Skubel et al.  
380 (2015) revealed that younger trees have more conservative water use strategies, while old trees showed  
381 greater variation in water use efficiency. Therefore, the effect might encompass both age and  
382 competition. Our experiment was conducted in an even-aged plantation, and the difference in height  
383 between the large- and small-diameter trees was not very obvious. Thus, the difference was mostly  
384 derived from the different growth rates and competition. Finally, in Martínez-Vilalta's research, the  
385 species, Scots pine, is sensitive to high temperature. In contrast, *P. tabulaeformis* can tolerate drought

386 and high temperature (Zeng et al., 2005). Therefore, differences in species characteristics and forest  
387 structure may also lead to differences in responses to drought.

388 In general, the  $R_c$  is negatively related to the  $R_t$  (Gazol et al., 2017) but positively related to  
389 increasing competition. For some species, increased competition leads to the reduction of radial growth  
390 (Hui et al., 2018), but the trees have high proportions of latewood and relatively thicker cell walls. And  
391 the tree with low growth rate also has low wood density and high hydraulic conductivity, which  
392 indicate a low susceptibility of suffering from hydraulic failure (Carnwath and Nelson 2016;  
393 Rungwattana and Hietz 2018). Thus, trees growing slowly have a greater ability to recover (Bréda et al.,  
394 2006; Martin-Benito et al., 2008; Montwé et al., 2015). However, Bottero et al. (2017) showed that the  
395  $R_c$  was negatively related to increasing densities in a ponderosa pine stand, which might be related to  
396 frequent thinning of their plots, especially for the plot with a low density (the intervals were 5-10  
397 years). Thinning can promote the growth of residual trees, and change their physiological  
398 characteristics, which can enhance tree recovery (Thomas et al., 2014; Kiorapostolou et al. 2020), and  
399 this physiological response can last up to 15 years for mature ponderosa pines (McDowell et al. 2003).  
400 In contrast, our plots were not thinned after the trees were planted. Thus, our results could avoid the  
401 effect of competition mixed with thinning.

402 Although competition modified tree response to drought, the effect of competition moderately  
403 increased tree sensitivity to drought under an intensively competitive environment. Some researchers  
404 also showed that the competition effect on restricting trees' radial growth faded under intensive  
405 competition (Gómez-Aparicio et al., 2011; Sánchez-Salguero et al., 2015; Dorman et al., 2015; Gonzá  
406 lez de Andrés et al., 2017). The calculation of response indices ( $R_t$ ,  $R_c$ ,  $R_s$ ) was based on radial growth.

407 Thus, the relationship between competition and response indices was also nonlinear. In addition,  
408 previous studies showed that the effect of competition decreased with an increase in water stress  
409 (Kunstler et al., 2011; Carnwath and Nelson, 2016). In the long term, trees living in high-density stands  
410 suffer from more serious drought stress than those living in low-density stands. To adapt to low soil  
411 water content they may maintain a lower ratio of leaf area to relative sapwood (Carnwath and Nelson.,  
412 2016). This characteristic is conducive to adapting to the increased water stress induced by increased  
413 competition

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

#### 423 **4.2 Response to interannual climate change**

424 The results also showed that the correlation between growth and interannual climate change was  
425 influenced by competition. The competition effect on their response was not constant throughout the  
426 whole period. In the early stage competition may have been at a low level. When they were young they  
427 had a smaller LAI than when they were mature so the demand for evapotranspiration was lower. And

428 the water deficit also was not very serious. So the competition effect was not evident. Besides, when  
429 they were young trees exhibited high stomatal conductance, photosynthetic rate, and high plasticity  
430 (Greenwood et al., 2008; David et al., 2018). Their speeding growth rate might cover the effect of  
431 increased competition. However, after 1999, it is obviously that the impact of competition reduced  
432 trees' sensitivity to climate change. This is consistent with previous research indicating that trees living  
433 in denser forests were not sensitive to climate change (Ford et al., 2016). In particular, the increase in  
434 competition caused trees to become insensitive to wet climate conditions (Carnwath and Nelson 2016).  
435 In crowded populations, high evapotranspiration leads to the increased moisture providing fewer  
436 benefits to individuals compared with low-density stands (Tamai et al., 2015). In high-density stands, a  
437 dense canopy and thick litter intercept some of the precipitation so that the effect of the climate  
438 becoming wetter was modulated (Motahari et al., 2013; Gerrits et al., 2010). Therefore, after 1999,  
439 although the MSPEI increased, growth at high density was less sensitive than that at low density and  
440 showed a relatively low growth rate. Reversely, Kunstler et al. (2011) reported that competition  
441 (increased density) had little impact on trees' climate sensitivity, possibly because changes in other  
442 factors moderated the impact of competition.

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

450 between diameters. Although it is a single-layer stand, its diameter distribution range is large (Table 1).  
451 In the even-aged stands the differences among small- and large-diameter trees were caused more by  
452 competition or other micro-environment differences. The lower sensitivity of small-diameter trees has a  
453 close relationship with the loss of plastic capacity induced by intensive competition (Linares et al.,  
454 2010). Our results also further demonstrated that small-diameter trees had a lower resilience (lower  $R_s$   
455 of small diameter trees in middle- and high-density stands, Fig. 2) than large-diameter trees. In addition,  
456 some research showed trees with low growth rates had higher water use efficiency and more rapid  
457 stomatal regulation than large trees (Zang et al., 2012; Martínez-Sancho et al., 2017), which helps them  
458 to mitigate the effects of drought stress. Therefore, small-diameter trees growth were less sensitive to  
459 the climate becoming wetter than that of large trees.

460 Competition among trees increased and negatively affected trees' response ability during the  
461 process of tree growth. Tree physiology also changes at different ages during this process (David et al.,  
462 2018). Besides, in their early stage the demand for water was lower. Thus in high-density stands, the  
463 small-diameter trees did not show an obvious increasing trend in a wet period (after 1999). Moreover,  
464 as density increased, the slope of the RBAI was obviously decreased. In the future, *P. tabulaeformis* in  
465 high-density stands will grow slower, and in dry spells, growth may be severely reduced, especially for  
466 small-diameter trees.

467 Overall, trees' sensitivity to interannual fluctuations in climate was influenced by competition. In  
468 this part, the effect of competition on tree responses to climate was not constant and might be  
469 associated with the change in trees' physiological characteristics and other factors, such as worsened  
470 soil conditions induced by overcrowded stems (Sun et al., 2018) and demands differing in different

471 stages. Further study is required to learn more about how tree physiology and competition affect tree  
472 responses to climate. Therefore, in the future, we should be paid more attention to physiological  
473 characteristics in different age classes and the combined effect of physiology and competition.

## 474 **5 Conclusion**

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

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