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Original Research Paper

Response of Radial Growth of *Pinus armandii* to Climate Change in the Qinling Mountains

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ABSTRACT

At present, there is limited research on the effect of climate change on the growth of trees in the Qinling Mountains, and the effect of altitude has rarely been considered. In order to accurately grasp the impact of climatic factors on the natural forest in this region, the effect of water and temperature conditions on the radial growth of *Pinus armandii* was studied according to dendroclimatology principles. Response function and multivariate regression methods were applied to study the response of the tree-rings, including earlywood width and latewood width, of *P. armandii* at three elevations (1600-1800, 1800-2000, 2000-2200 m) to climate change in this region. The results showed that the radial growth of *P. armandii* at the three elevations contained rich climatic information. The tree-ring widths at the three elevations were significantly negatively correlated with September temperature of the previous year and May temperature of the current year ($P < 0.05$) and were also negatively correlated with August precipitation of the previous year and May precipitation of the current year. The late-wood width of *P. armandii* at 1600-1800 m and 1800-2000 m was less sensitive to temperature and precipitation than that of the earlywood. The latewood width of *P. armandii* at 2000-2200 m was significantly negatively correlated with December temperature of the previous year and May temperature of the current year ($P < 0.01$), and was significantly and positively correlated with August precipitation of the previous year ($P < 0.05$). Characteristic analysis of the special years showed that large quantities of precipitation in September and October of the previous year were more likely to result in the formation of a very wide tree-ring. High spring and summer temperatures and less precipitation from April to June more likely resulted in the formation of extremely narrow tree-rings. Therefore, high precipitation in autumn of the previous year was conducive to the growth of *P. armandii*, whereas high temperature and drought in spring and summer inhibited the growth of *P. armandii*.

INTRODUCTION

Climate change is a serious global environmental problem. Climate warming and the frequency of extreme weather events have resulted in a tremendous and negative impact on human society, threatening human survival and social and economic sustainable development (Shang et al. 2015), as well as causing considerable damage to the environment. Forests are an essential part of the terrestrial ecosystem and are sensitive to climate change (Yude et al. 2011, Piao et al. 2012, Duncan et al. 2015). Numerous studies have shown that tree-rings record information of past climate change (Jörg et al. 2013, Mazza et al. 2014). A large number of correlation analyses between tree-ring width and climate factors showed that the ring width had a complicated relationship with climate factors, which was considered to be affected by climate factors and tree growth rhythm (Devi et al. 2008, Neukom & Gergis 2012, Estela et al. 2016). When water was the limiting factor for the growth of trees, ring width was often positively related to precipitation; however, when water was sufficient or excessive, ring width was uncorrelated or negatively correlated with precipitation (Xu et al. 2012, Dario et al. 2013). The influence of temperature on the growth of trees is more complex. A small increase in temperature at the start of the growing season extends the growing season, but during the flourishing season, temperature is often no longer a limiting factor. Excessively high temperatures increase transpiration, leading to the negative correlation between ring width and temperature (Eilmann et al. 2009, Dick et al. 2014).

The Qinling Mountains are located in the centre of China and belong to the warm temperate and subtropical climate transition zone. This region is also a typical fragile ecological environment. Due to global climate change, obvious changes in temperature, precipitation and evaporation of the Qinling Mountains have been observed (Yin 2002). In the last 50 years, the temperature of the Qinling Mountains has continuously increased, especially since the 1980s when the mean annual temperature increased obviously (Yan & Zheng

2001, Song et al. 2011) at 0.15-0.24°C/10 a, especially on the north facing slope of the Qinling Mountains with a rate as high as 0.74°C/10 a (Bai et al. 2012). These studies showed that different tree species in the Huoditang forest region of the Qinling Mountains were significantly different ($P < 0.05$) in their response to climate change (Yang et al. 2014). Increased temperatures and precipitation both contributed to an increase in vegetation net primary productivity in most parts of the south facing slope of the Qinling Mountains, but for most districts, there was no significant effect (Jiang et al. 2012). In 1994, Shao's research on *P. armandii* chronology in the eastern Qinling Mountains (Shao & Wu 1994), and Kang's research on timberline trees of *Larix chinensis* in the Taibai Mountains showed that the tree-ring index and March precipitation were positively correlated (Kang et al. 2010). However, these studies were focused on the effects of climate factors on the growth of trees at the same altitude and could not reflect the influence of the vertical change of the climate on the radial growth of trees.

P. armandii is the most widely distributed tree species in natural forests on the Qinling Mountains. This study analysed the regular patterns of moisture and temperature conditions on the growth of *P. armandii* at different altitudes in the Qinling Mountains and revealed the effect of climate change on the growth of natural forests in this area. The results could lay a foundation for future studies on the influence of climate change on the vertical distribution of the tree species and on the ecosystem structure of the Qinling Mountains.

MATERIALS AND METHODS

In August 2013, we sampled 210 increment cores from 105 healthy *P. armandii* trees at three elevations (1600-1800 m, 1800-2000 m, 2000-2200 m); two cores were extracted from each tree at breast height in the Huoditang forest region on the southern slope of the Qinling Mountains. The sampling tool was an incremental borer (diameter: 5.15 mm). Table 1 shows the basic information of the sampling plots.

All climatic data were obtained from the National Meteorological Information Centre (http://cdc.cma.gov.cn/) and the weather station of Ningshan County nearest to the sampling sites, Shaanxi Province. The weather station of Ningshan lies at longitude E: 108°19', latitude N: 33°19' and

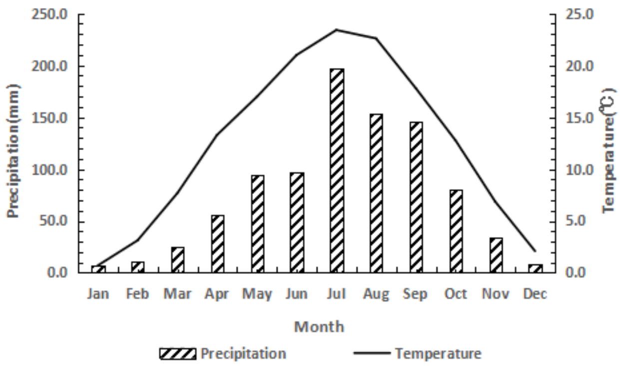

Fig. 1: Long-term (1958-2013) mean temperature (MT) and precipitation (MP) of Ningshan.

altitude 802.4 m; the mean annual temperature is 12.4°C (1958-2013). January is the coldest month (0.7°C) and July is the warmest month (23.4°C). Total annual precipitation is 909.0 mm with the least amount of rainfall (7.4 mm) occurring in January and the most (197.2 mm) in July (Fig. 1).

Ring widths were measured with the WinDENDROTM 2005a image analysis system; tree-ring width measurements were cross-dated at the same time. The cross-dated tree-rings were then checked by the auxiliary program COFECHA (Yang et al. 2014). This eliminated some poor correlation samples and improved the quality of the tree-ring chronologies (Hunt & Martin 1991). We completed response function analysis using SPSS software, with annual ring width as the dependent variable. The monthly average temperature, monthly average precipitation, and principal component scores of the previous year's annual ring width were the independent variables. The multiple regression analysis was performed using the stepwise regression method.

By using a multiple regression equation and the expression between the principal component scores and climate variables, we calculated the response function between annual tree-ring width and climate factors (Elisabeth et al. 2013). The impact of extreme weather on tree growth is difficult to identify in correlation analysis (Tolwinski-Ward et al. 2015), extremely wide and narrow years were further analysed, and related analyses results were independently checked (Panayotov et al. 2010).

Table 1: Basic information of the sample plots.

Elevation (m)	Longitude	Latitude	Number of trees	Stand age (a)	Canopy density	Slope (°)	Aspect
1600-1800	E108°272	N33°262	38	29-63	0.6-0.8	30	WS
1800-2000	E108°272	N33°272	37	33-52	0.6-0.8	40	N
2000-2200	E108°292	N33°292	30	39-60	0.6-0.7	30	ES

Table 2: Statistics of radial growth of *P. armandii* growing at three elevations.

Radial growth	Elevation (m)	Mean (mm)	Maximum (mm)	Standard deviation (mm)	First autocorrelation
Ring width	1600-1800	3.569	4.979	0.859	0.61**
	1800-2000	3.659	4.636	0.641	0.74**
	2000-2200	3.310	4.578	0.637	0.69**
Earlywood width	1600-1800	2.749	4.002	0.741	0.57**
	1800-2000	2.816	3.577	0.563	0.78**
	2000-2200	2.470	3.696	0.625	0.63**
Latewood width	1600-1800	0.822	0.996	0.160	0.41**
	1800-2000	0.843	0.932	0.210	0.38**
	2000-2200	0.840	0.916	0.157	0.53**

Note: *P<0.05; **P<0.01.

Table 3: Statistical characteristics of tree-ring standard chronology.

Characteristic parameter	Elevation (m) 1600-1800			1800-2000			2000-2200		
	R	*EW*	*LW*	*R*	*EW*	*LW*	*R*	*EW*	*LW*
MS	0.322	0.341	0.302	0.245	0.281	0.212	0.198	0.214	0.187
EPS	0.934	0.954	0.921	0.947	0.943	0.922	0.927	0.910	0.923
SNR	23.584	20.897	16.984	17.640	15.120	11.380	11.817	9.242	10.372
R_1	0.793	0.731	0.723	0.758	0.745	0.755	0.701	0.713	0.725
PC_1	0.541	0.463	0.312	0.457	0.329	0.295	0.313	0.241	0.265

Note: *R* represents the annual ring width, *EW* represents early-wood width, and *LW* represents late-wood width.

RESULTS AND DISCUSSION

The basic characteristics of the radial growth of *P. armandii*: Table 2 shows that when *P. armandii* was at an altitude of 1600-1800 m, the standard deviation of the early-wood width (0.741mm) and annual ring width (0.859mm) were both the largest, and the annual ring width and early-wood width at this altitude range varied considerably. The autocorrelation coefficients of ring width at the three different altitudes ranged from 0.38-0.78mm. This suggests that the growth of *P. armandii* in the study area was strongly influenced by tree growth during the previous year. Consequently, the growth of *P. armandii* had a lag effect. According to the laws of the growth of *P. armandii* and the tree growth lag effect, we used May of the previous year to December of the current year as a climate period.

Statistical characteristics of the tree-ring standard chronology of *P. armandii*: Tree-ring width contains genetic and environmental information. To explore the growth-climate relationships of *P. armandii*, data were analysed with the program ARSTAN, which was downloaded from the Tree-Ring laboratory of Columbia University (www.Ideo. columbia.edu/ tree-ring-laboratory). This research adopted a 5-year sliding average value method (Peng, et al. 2013). The ARSTAN program established the tree-ring standard chronology, and the calculation of parameters related to standard chronology was also completed (Table 3).

The mean sensitivity (*MS*) decreased with an increase in altitude, and the annual ring width varied from 0.198-0-322. The early-wood and late-wood widths at the 1600-1800 m elevation had the highest sensitivity, greater than 0.3. Thus, we conclude that *P. armandii* tree rings contain rich climate information. Larger signal-to-noise ratio (SNR) chronology contains more climate information. The *SNR* (23.584) of the annual ring width chronology at the 1600-1800 m altitude is the highest, which is consistent with the results of the *MS* analysis. According to the parameters in Table 3, *MS* and *SNR* are both relatively high, illustrating that the impact of climate factors on tree growth is large and that the tree-ring standard chronology contains rich climate information.

Response of tree-ring width chronologies of *P. armandii* to climate factors: The correlation analysis between ring-width chronologies and monthly average temperature and precipitation of one climate research year (*L*5-*L*12 and *T*1-*T*12) is presented in Table 4 and Table 5. From the correlation coefficient between average monthly temperature and the chronology, it can be concluded that the tree-ring width had a basically negative correlation with average monthly temperature. The annual tree-ring width at the 1600-1800m

Table 4: Correlations between monthly average temperature and chronologies.

Month	Elevation (m)								
	1600-1800			1800-2000			2000-2200		
	R	*EW*	*LW*	*R*	*EW*	*LW*	*R*	*EW*	*LW*
*L*5	-0.191	-0.129	-0.184	-0.105	0.023	0.034	-0.162	-0.103	-0.231
*L*6	0.013	0.035	0.055	-0.107	-0.043	-0.100	0.062	-0.097	-0.115
*L*7	-0.036	0.022	0.005	-0.110	0.009	-0.205	-0.213	-0.159	-0.201
*L*8	-0.124	-0.175	-0.19	-0.201	-0.165	-0.141	-0.186	-0.089	-0.176
*L*9	-0.33*	-0.380*	-0.169	-0.314*	-0.254	-0.189	-0.303*	-0.133	-0.127
*L*10	0.049	0.06	0.018	0.027	-0.008	-0.203	-0.284	-0.197	-0.337
*L*11	-0.33*	-0.285	-0.190	-0.131	-0.052	-0.296	-0.103	-0.232	-0.182
*L*12	-0.169	-0.145	-0.191	-0.072	-0.038	-0.156	-0.183	-0.155	-0.335*
*T*1	-0.037	-0.123	-0.152	0.055	-0.177	-0.014	-0.018	0.030	0.006
*T*2	-0.110	-0.061	-0.054	-0.053	-0.105	-0.159	-0.034	-0.137	0.068
*T*3	-0.118	-0.159	0.091	-0.107	-0.125	-0.281	-0.199	-0.143	-0.283
*T*4	-0.304*	-0.109	-0.063	-0.336*	-0.103	-0.119	-0.063	-0.076	-0.134
*T*5	-0.338*	-0.229	-0.184	-0.425**	-0.185	-0.176	-0.415**	-0.130	-0.405**
*T*6	-0.213	-0.235	-0.104	-0.121	-0.043	-0.101	0.062	0.097	-0.115
*T*7	-0.036	0.022	0.005	-0.110	0.009	-0.205	-0.213	-0.159	-0.201
*T*8	-0.198	-0.154	0.019	-0.181	-0.065	-0.141	-0.172	0.089	-0.176
*T*9	-0.266	-0.264	-0.339*	-0.169	-0.274	-0.228	-0.209	-0.137	-0.113
*T*10	0.059	-0.06	-0.018	-0.027	-0.008	-0.203	-0.284	-0.197	-0.237
T11	-0.056	-0.095	-0.093	-0.134	-0.073	-0.099	-0.110	-0.052	0.085
*T*12	-0.059	-0.049	-0.190	-0.072	-0.038	-0.013	-0.083	-0.055	-0.035

Note: T1-T12 represent the months from January to December of the current year. L5-L12 represent the months from May to December of the previous year. R represents the annual ring width, EW represents early-wood width, LW represents late-wood width, *Significant difference at the 0.05 level; **Significant difference at the 0.01 level.

Table 5: Correlations between monthly precipitation and chronologies.

Month	Elevation (m)								
	1600-1800			1800-2000			2000-2200		
	R	*EW*	*LW*	*R*	*EW*	*LW*	*R*	*EW*	*LW*
*L*5	-0.099	-0.07	-0.068	0.144	0.118	0.157	0.172	0.113	0.165
*L*6	0.099	0.112	0.143	-0.067	-0.029	0.049	0.168	0.048	0.156
*L*7	0.252	0.124	0.268	0.259	0.032	0.215	0.182	0.130	0.237
*L*8	0.403**	0.367*	0.091	0.357*	0.329*	0.145	0.314*	0.178	0.323*
*L*9	0.116	0.067	0.145	0.334*	0.192	0.111	0.095	0.157	-0.012
*L*10	0.112	-0.102	-0.12	-0.018	0.071	-0.019	-0.088	0.026	-0.067
*L*11	0.147	0.167	0.105	0.116	0.058	0.101	0.056	0.023	0.055
*L*12	0.118	0.123	0.178	-0.03	-0.011	0.129	0.118	0.087	0.121
*P*1	0.058	0.094	0.012	0.077	0.074	0.102	0.058	0.063	0.082
*P*2	0.183	-0.148	-0.088	-0.015	0.107	0.110	-0.084	-0.079	0.223
*P*3	0.044	0.081	0.058	0.115	0.076	0.044	0.034	-0.047	0.09
*P*4	3.612*	-0.069	0.165	0.079	0.137	0.109	-0.067	-0.071	0.199
*P*5	0.348*	0.346*	0.145	0.324*	0.177	0.094	0.279	0.128	0.039
*P*6	-0.018	-0.001	-0.055	-0.107	-0.025	-0.06	0.315*	0.033	-0.013
*P*7	0.062	0.101	0.082	0.098	0.166	0.093	0.175	0.191	-0.094
*P*8	0.324*	0.06	0.074	0.052	0.087	0.046	0.179	0.137	0.162
*P*9	0.151	0.058	0.144	0.106	0.187	-0.009	-0.014	0.05	0.089
*P*10	0.118	0.175	0.115	0.026	0.019	0.052	0.074	0.106	0.044
*P*11	0.108	0.011	0.171	0.093	0.087	0.104	0.131	0.185	0.144
*P*12	-0.037	-0.094	0.118	-0.019	0.104	-0.017	0.056	0.103	0.039

Note: P1-P12 represent the months from January to December of the current year. L5-L12 represent the months from May to December of the previous year. R represents the annual ring width, EW represents early-wood width, LW represents late-wood width, *Significant difference at the 0.05 level; **Significant difference at the 0.01 level.

altitude was significantly negatively correlated with the September and November temperatures of the previous year and April-May temperatures of the current year (P <0.05). The annual tree-ring width at the 1800-2000 m altitude had a significant correlation with the May temperature of the current year (P <0.01), whereas the early-wood and late-wood widths were not significantly correlated with temperature. At an altitude of 2000-2200 m, the annual ring width was significantly correlated with the September temperature of the previous year, whereas the late and early-wood widths were significantly correlated with the May temperature of the current year.

The correlation coefficient of monthly precipitation and chronology are listed in Table 5, indicating that the ring width had a basically positive correlation with precipitation. The August-September precipitation of the previous year and the May-August precipitation of the current year had an obvious influence on the ring width of *P. armandii* at the three elevations. In addition, the August precipitation of the previous year had a significantly positive correlation with tree-ring width at an altitude of 1600-1800 m (P < 0.01). At an altitude of 2000-2200 m, the ring width was significantly and positively correlated with June precipitation of the current year (P< 0.05).

The ring width can be explained by climate change variables: Through principal component analysis, the meteorological data and the previous year's tree-ring width were classified into 9 principal components. Five principal components with a characteristic root value above 1.0 accounted for a cumulative contribution rate of 67.13% (Table 6), achieving the goal of intensive information. These 5 principal component scores served as the independent variables and the ring width index served as the dependent variable.

Table 6: Eigen values and proportional and cumulative values of climate variance.

Principal component	Eigen value	Proportion (%)	Cumulative (%)
No.1	2.614	20.107	20.107
No.2	2.010	15.464	35.571
No.3	1.661	12.781	48.352
No.4	1.308	10.060	58.412
No.5	1.134	8.721	67.13

Table 7: Results of the multiple regression analysis.

Principal component	Standard partial regression coefficients
No.1	-0.493
No.2	0.374
No.5	-0.321
Decision coefficient R^2 (%)	45.7

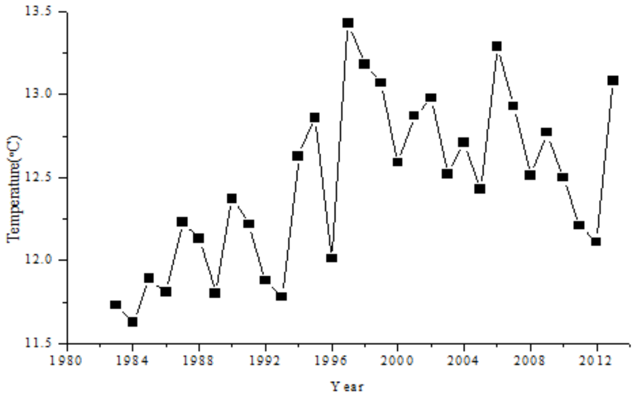

Fig. 2: Annual mean temperature for the common interval from 1983 to 2013.

In addition, the stepwise regression method was used in multiple regression analysis. The results are listed in Table 7.

According to the analysis of the temperature change in the study area, the temperature from 1983 to 2013 had an obvious increasing trend (Fig. 2) and increased at the rate of 0.67°C/10 a. This information was used to construct the response function of annual ring width and temperature and precipitation over the period from 1983 to 2013 and was used to establish preliminary estimates of the global warming impact on *P. armandii*.

As the growth *P. armandii* is a result of the combined action of temperature and precipitation, multivariate regression was used to describe the relationship between tree-ring width and temperature and precipitation. April to September is the growing season of *P. armandii*. The correlation among the average temperatures from April to September of the current year, the tree-ring width chronology of the previous year (xi-1) and the data were tested with multiple linear stepwise regressions. When the corresponding monthly precipitation from April to September was the same (at a 95% confidence interval), the regression equations were as follows:

$$f_T = -0.242T_4 - 0.178T_5 - 0.109T_8 + 0.167T_9 + 0.397x_{i-1} + 7.958(R = 0.626, R^2 = 0.523, F = 14.949, P < 0.05) \quad ...(1)$$

$$f_p = 0.0034P_4 + 0.0046P_5 + 0.0032P_6 - 0.0014P_9 + 0.4631x_{i-1} + 7.582(R = 0.613, R^2 = 0.419, F = 13.390, P < 0.05) \quad ...(2)$$

In the response function equations (1) and (2), ft and fp represent the response function of the annual tree-ring width with temperature and precipitation, respectively. Meanwhile, xi represents the tree-ring width of the previous year, i =

Table 8: The analysis of characteristic years.

Characteristic	Year	Temperature	Precipitation
Wide rings	1976	The lowest annual average temperature, spring and summer were relatively low	September of the past two years and April to May of the current year were relatively high
	1979	Spring was relatively low	May was relatively high
	1980	Summer was relatively low	October of the previous year and April of the current year were relatively high
	1989	The lowest annual average temperature; spring and summer were relatively low	April was relatively high
Narrow rings	1973	Spring was relatively high	May was relatively low
	1995	Summer was relatively high	April to May were relatively low
	2004	Spring was relatively high	April to May and July to August were relatively low
	2006	The highest annual average temperature; summer and autumn were relatively high	The annual rainfall was the lowest; April, July and August were relatively low
	2007	Spring was relatively high	April and September were relatively low
	2012	Spring and summer were relatively high	April and June were relatively low

1983, 1984... 2012; T4, T5, T8 and T9 represent the average temperature of April, May, August, and September, respectively. Similarly, P4, P5, P6, P7 and P8 represent the mean month precipitation for the respective months. The respective coefficients of determination (R2) of the two equations are 0.523 and 0.419; the f values are 14.949 and 13.390, which are both within the 95% confidence interval.

Temperature and precipitation are the main climate factors that limit the growth of *P. armandii*. Precipitation in the growing season from April to August, with April to June being the most critical of these months, shows that the previous year's precipitation also had a certain influence on tree growth. Compared with the impact of the previous year's precipitation on tree growth, the influence of temperature was smaller and only occurred at the beginning of the growing season in April, May and August. A comparison of the measured and simulated values of precipitation and temperature indicated that the average temperature tallies with the response of tree-ring widths to climate.

The analysis of the special years: In the characteristic analysis of the special years, the goal was to determine the extremely narrow and wide years. During these years, if the spring and summer temperatures were low and the September to October precipitation of the previous year was high, a wide annual ring would most likely be observed; if the spring and summer temperatures were high and the growing season (April to June) precipitation was low, this would more easily lead to an extremely narrow annual ring (Table 8).

CONCLUSIONS

For the purpose of forecasting the effects of climate change on the growth of natural forests in the Qinling Mountains, the radial growth of *P. armandii* at different altitudes was studied by using dendrochronology and mathematical modelling. The main conclusions were as follows:

The early-wood and late-wood width standard chronology of *P. armandii* at three elevations was relatively high (MS:0.187-0.341, SNR:9.242-23.584), indicating that the meteorological factors significantly affected the radial growth of *P. armandii*, and the chronology contained rich information.

Tree-ring width was negatively correlated with monthly average temperature and was positively correlated with monthly precipitation. The radial growth of *P. armandii* at low and medium elevations (1600-2000 m) was mainly affected by precipitation, while at high elevations (2000-2200 m) mainly affected by temperature. This indicated that temperature was the main factor affecting the growth of the trees in the upper limit of the distribution area, while precipitation was the main factor affecting the growth of the trees in the lower limit of the distribution area. A comparison of the simulated values from the response function equation for tree-ring width in relation to precipitation and temperature with the actual measured values showed that the average temperature tallied with the response of tree-ring growth to climate.

The characteristic analysis of the special years indicated that a lower temperature in spring and summer of the current year and a high amount of precipitation from September to October led to the formation of a very wide annual tree-ring, while a higher temperature in spring and summer and low precipitation from April to June in the current year led to the formation of an extremely narrow tree-ring. Therefore, a cool and humid climate was conductive to the radial growth of *P. armandii* in the growing season.

The tree growth models proposed in this study can predict the future changes in the distribution of *P. armandii* and can also provide a theoretical basis for forestry to deal with climate change. Further research on the models, especially in other distribution areas of *P. armandii*, is needed.

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