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Daily variations in radial growth of *Pinus massoniana* trunk and its response to precipitation

Jing Cui[a], Zhenhua Li[b,*], Yaoqing Sun[a], Shicheng Zhao[a], Qingsong Zhu[c], Jiapeng Shen[a]

[a]*School of Forestry, Xinyang Agriculture and Forestry University, Xinyang 464100, China*
[b]*School of Civil Engineering and Architecture, Xinxiang University, Xinxiang 453000, China, email: lzhh2016@126.com*
[c]*School of Horticulture, Xinyang Agriculture and Forestry University, Xinyang 464100, China*

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ABSTRACT

The response of tree growth to precipitation has long been a focal point in forest ecology. Previous studies based on tree ring analysis have mostly focused on annual scales, while research at finer temporal scales is still lacking. This limitation hampers the improvement of forest vegetation recovery and management in drought-prone areas. In this study, a high-resolution dendrometer was employed to monitor the daily variations in trunk diameter of the drought-tolerant species, *Pinus massoniana*. Additionally, the relationship between diameter increment and precipitation for trees of different sizes was quantitatively analyzed. The results revealed the following findings: (1) diameter increment initially increased rapidly and then gradually stabilized in a non-linear manner as precipitation increased. The critical threshold and final stable values differed among trees of different sizes. The relationship between diameter increment (y_1) and precipitation (x_1) could be described and predicted using the Logistic Regression Model $y_1 = a - b \times \text{EXP}(c \times x_1)$, with a good fit ($R^2 > 0.82$). (2) For precipitation events of the same magnitude, the order of diameter increment was spring > summer > autumn. (3) Tree size (diameter at breast height, x_2) positively correlated with diameter increment (y_2), and the relationship was highly significant ($P < 0.01$). The linear function between the two variables was $y_2 = 0.0113x_2 - 0.0727$ ($R^2 = 0.95$). In conclusion, the daily variations in trunk diameter of *P. massoniana* were significantly influenced by precipitation. Diameter increment increased with higher precipitation levels, following a logistic-type non-linear pattern. Furthermore, tree size played a significant role, as larger trees exhibited greater diameter increments in response to precipitation.

Keywords: Pinus massoniana; Radial daily variation; Precipitation; Tree size variation

1. Introduction

Pinus massoniana is one of the primary tree species used for afforestation in subtropical regions of China. It plays a crucial role in vegetation restoration, soil and water conservation, and water resource management, contributing significantly to ecological and economic value [1,2]. However, due to limited water resources and inadequate vegetation carrying capacity, some forest stands experience reduced growth potential and low productivity as they age [3]. This not only hinders the sustained provision of ecosystem services but also poses a threat to the stability of local forest and grassland vegetation systems and their equilibrium with the soil and water environment [4,5]. Therefore, conducting in-depth research and quantitatively understanding the relationship between the growth of *P. massoniana* and water resources is of paramount importance.

The growth and development of *P. massoniana* are influenced by various factors, including the biological characteristics of the tree species, site conditions, and silvicultural

* Corresponding author.

practices. Additionally, external environmental factors such as light, temperature, and precipitation have a significant impact [6,7]. Studies have found a significant negative correlation between the width of annual rings in *Picea schrenkiana*, a species found in the Tian Shan mountain region, and the temperature during the growing season [8]. Xiong et al. [9] research on radial growth of *Larix principis-rupprechtii* on the southern slope of Liupanshan mountains suggests that temperature and precipitation are the main factors influencing radial growth in this species [9]. Other scholars have studied the relationship between growth of tree species such as *Pinus sylvestris*, *Melia azedarach*, *Robinia pseudoacacia*, and *Pinus tabulaeformis* and meteorological factors, with results indicating a significant influence of climatic conditions on tree growth [10–13]. From a physiological perspective, the radial variation process in *P. massoniana* is closely related to its internal water status. When the root system has sufficient water uptake, the stem diameter slightly expands, while water deficiency causes slight shrinkage in stem diameter. Therefore, changes in stem diameter can be used to diagnose the water status of the tree [14,15]. Currently, there is relatively limited research on the response of radial daily variation in *P. massoniana* to precipitation, the functional relationship between radial variation caused by precipitation and tree size, as well as the functional relationship between radial variation and precipitation [15].

Therefore, this study aims to use dendrometers to continuously and non-destructively observe the variations in stem diameter of *P. massoniana* in the Jigongshan National Nature Reserve. The objectives are as follows: (1) to analyze the daily radial variation process of the stem diameter and reveal the response characteristics of *P. massoniana* in the northern subtropical region to precipitation; (2) to quantitatively understand the effects of factors such as precipitation amount, precipitation time distribution, and individual tree differences on the stem diameter increment of *P. massoniana*. These studies will contribute to a better understanding of the response characteristics of the daily radial variation in stem diameter of *P. massoniana* to precipitation in the northern subtropical region, providing scientific references for the silvicultural management of *P. massoniana* in this region.

2. Materials and methods

2.1. Overview of the research area

The Jigongshan National Nature Reserve, located within the boundaries of Xinyang, Henan Province, China (114°01′–114°06′ E, 31°46′–31°52′ N), boasts a mountainous terrain that stretches in an east-west direction. Encompassing an area of approximately 2,917 ha, this reserve ranges in relative altitudes from 120 to 810 m. The soil composition predominantly consists of yellow-brown soil, with a thickness of around 30 cm and a pH value ranging from 5.0 to 6.5. Situated on the fringes of the northern subtropical region, the Jigongshan National Nature Reserve exhibits distinctive characteristics of both a monsoonal and mountainous climate. The four seasons are clearly demarcated, with an average annual temperature of 15.2°C. The extreme temperature ranges from a scorching 40.9°C to a chilling –20°C. During the summer season, the average temperature rises to 23.7°C. The accumulated thermal sum (≥10°C) reaches 4,881°C-d annually, while the frost-free period spans 220 d. Moreover, the average annual precipitation is recorded at 1,118.7 mm. Within the reserve's boundaries, the dominant vegetation type is characterized as subtropical evergreen broad-leaved forest, primarily comprised of artificial forests and secondary growth. Notably, there exists a substantial expanse of artificial *P. massoniana* forests [16].

2.2. Monitoring of stem diameter

During the period from May to October 2021, a standard plot measuring 20 m × 20 m was established within the pure *P. massoniana* forest in the Jigongshan National Nature Reserve. Within this plot, six individual *P. massoniana* trees of varying sizes and in good health were selected for continuous diameter growth observations. Details of the sample trees are provided in Table 1.

The diameter growth of the six selected *P. massoniana* trees was continuously monitored for 24 h using a DC-type stem circumference recorder (Ecomatik GmbH, Germany). The use of a dendrometer allows for the automatic and continuous recording of radial growth changes in trees over short time periods, corresponding to synchronous observations of meteorological factors. This method demonstrates significant advantages in studying tree growth and its relationship with climate [17,18]. At regular intervals of 7 d, the portable computer was connected to the data logger to download and collect the raw data of the radical changes in stem. The recorded data represents the net change in diameter, excluding the initial diameter at the installation position. The data sampling frequency was set at 5 min/recording.

2.3. Monitoring of precipitation process

Adjacent to the *P. massoniana* forest, an automatic weather station (Weatherhawk-232, United States) was installed in an open area to continuously monitor various meteorological factors throughout the year. These factors include solar radiation intensity, air temperature, humidity, wind speed, and precipitation. The data were recorded at a frequency of 5 min/recording, allowing for a fine-grained analysis of precipitation events. Additionally, a siphon-type self-recording rain gauge and a standard rain gauge were placed nearby to provide supplementary measurements of precipitation.

Table 1
Basic information of *Pinus massoniana* sample

No.	Diameter at breast height (cm)	Tree height (m)	Breadth (m)
18	19.8	12.2	5.2 × 4.9
82	14.2	11.9	4.3 × 3.8
54	11.5	11.1	3.6 × 3.9
49	13.8	14.5	4.4 × 3.5
46	15.7	12.3	4.7 × 4.1
48	13.1	11.5	4.1 × 3.3

2.4. Data statistics and analysis

The tree trunk diameter increment can be calculated as the difference between the maximum tree trunk diameter recorded on a given day and the maximum tree trunk diameter recorded on the previous day.

The data was organized and preliminarily analyzed using Microsoft Excel. For the purposes of correlation analysis, non-linear curve fitting, and regression analysis, the software SPSS 19.0 was employed. The goodness of fit of different function equations was assessed by comparing the magnitude of the coefficient of determination (R^2). To evaluate the statistical significance of the precipitation data, a one-way analysis of variance was conducted, and a *t*-test analysis was performed with a significance level set at $P < 0.05$.

3. Results and analysis

3.1. Relationship between precipitation and daily variation of trunk diameter

From Fig. 1, it can be observed that during the growth season from May to October, the daily variation in trunk diameter of *P. massoniana* exhibits a rapid initial growth followed by a gradual slowdown. This pattern can be categorized into three distinct stages: (1) the rapid growth stage (May 11–July 6), during which the trunk diameter shows rapid growth; (2) the slow growth stage (July 7–August 17), where the trunk diameter continues to increase but at a noticeably slower rate. In periods of low precipitation or consecutive sunny days, there is a phenomenon of trunk diameter shrinkage; (3) the stagnant growth stage (August 18–October 26), during which the trunk diameter remains relatively stable without further thickening. It is evident that the six selected *P. massoniana* trees exhibit similar trends in trunk diameter variation, all displaying these three growth stages.

From Fig. 1 it is evident that each instance of precipitation has a significant positive impact on trunk diameter, with larger precipitation amounts corresponding to greater trunk diameter increments. Furthermore, there are variations in trunk diameter increments among different tree samples, even within the same time period. Therefore, to gain a deeper understanding of the response mechanism of radial tree growth to precipitation, it is necessary to further investigate the influences of factors such as precipitation magnitude, seasonal precipitation patterns, and individual tree differences on trunk diameter increments.

In Fig. 2, taking dominant tree sample No. 18 as an example, the difference in trunk diameter increments during precipitation and non-precipitation periods is compared. It can be observed that the trunk diameter increments during precipitation periods are higher than those during non-precipitation periods (negative values are present). Additionally, the trunk diameter increments of *P. massoniana* show a gradual decrease with changing seasons, particularly during precipitation periods where the decrease in trunk diameter increments is more pronounced. This indicates that while precipitation has a stimulating effect on trunk diameter increments, it is also influenced by seasonal variations.

3.2. Response of trunk diameter increment to precipitation

To quantitatively understand the response characteristics of trunk diameter increments to precipitation, the collected raw data on precipitation and radial tree growth were analyzed using Excel. A scatter plot depicting the relationship between *P. massoniana* trunk diameter increments and precipitation was generated as shown in Fig. 3.

According to the scatter plot depicted in Fig. 3, trunk diameter increments exhibit a characteristic pattern of rapid initial growth followed by a slower rate of increase as precipitation amounts increase. The crucial threshold value,

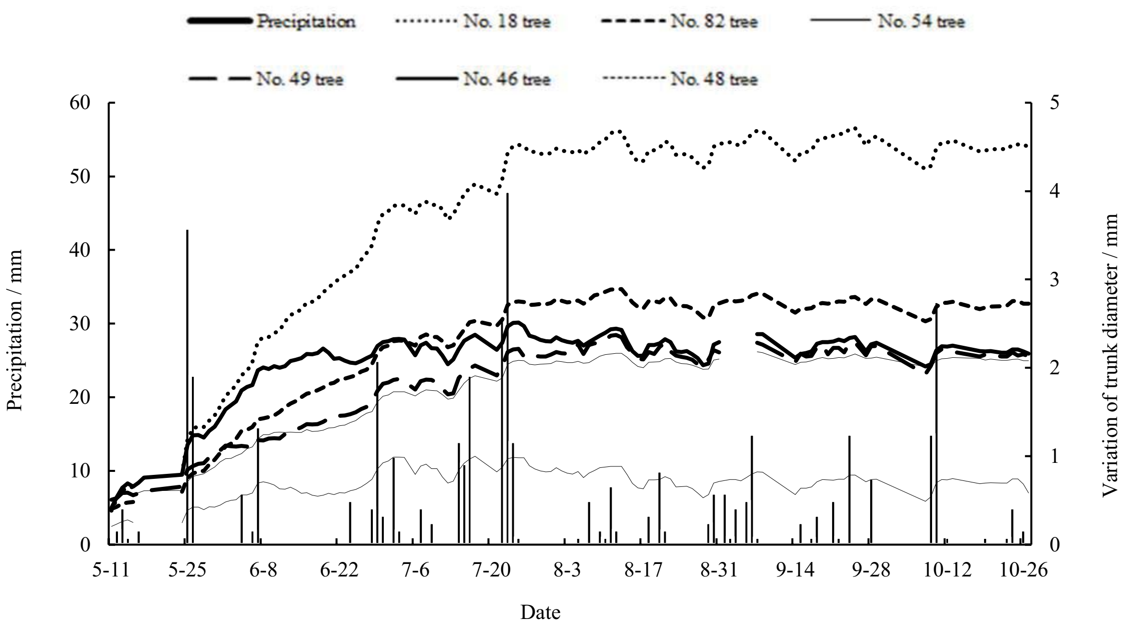

Fig. 1. Daily variation of precipitation and trunk diameter.

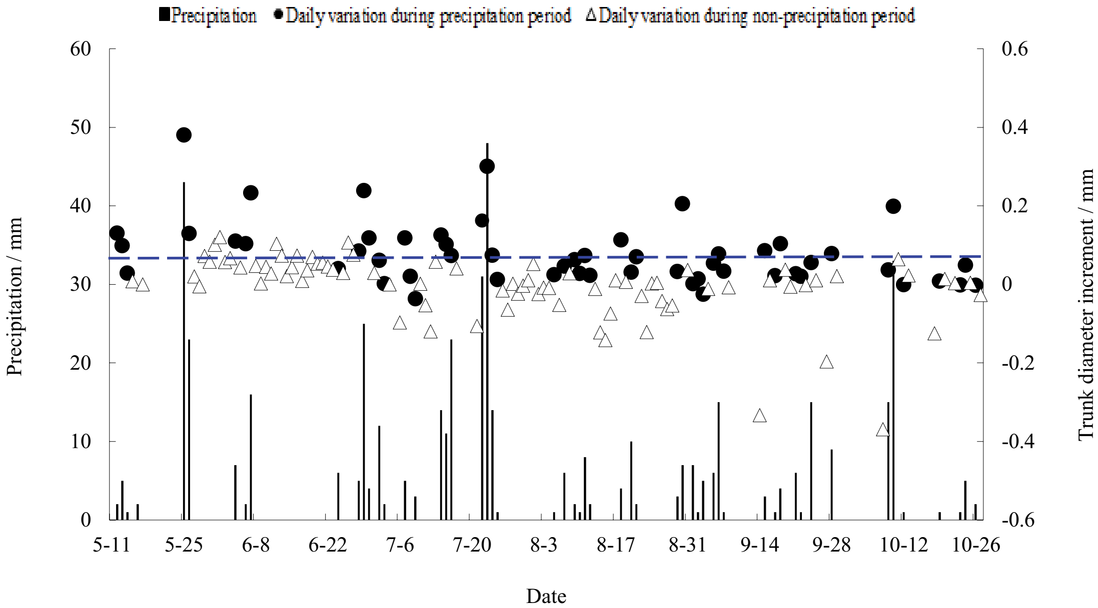

Fig. 2. Relationship between precipitation and increment of trunk diameter.

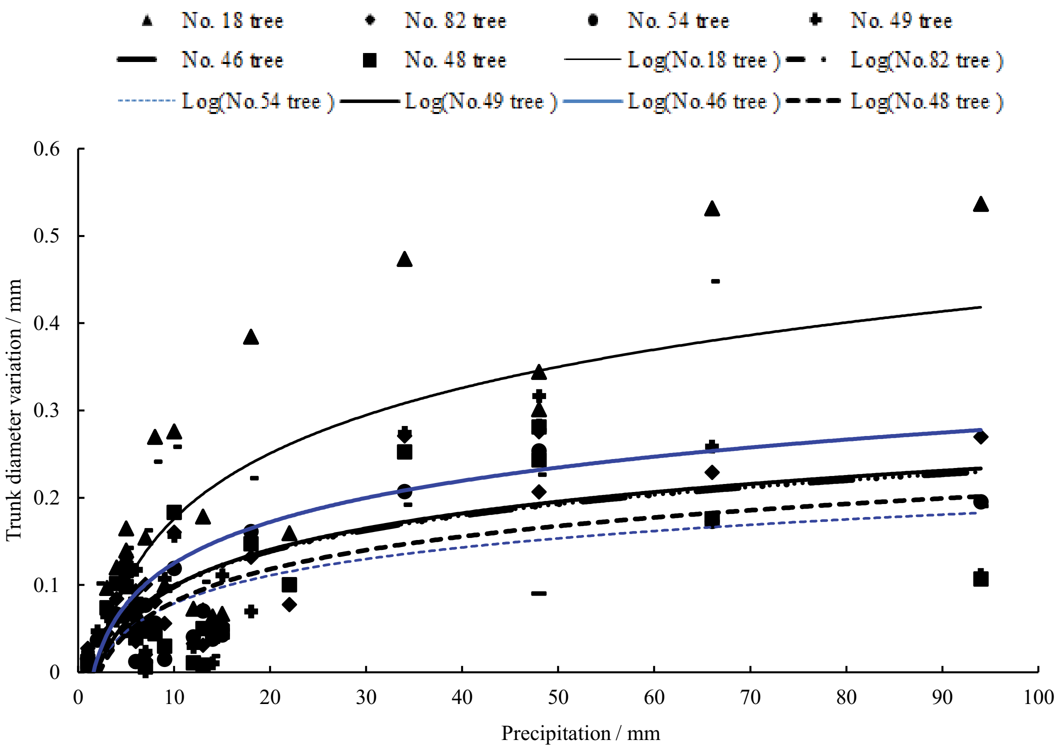

Fig. 3. Response of trunk diameter increment to precipitation.

which represents a critical transition point, is approximately 10 mm. Specifically, for precipitation amounts ranging from 0 to 10 mm, an increase in precipitation leads to a rapid growth in trunk diameter increments. When precipitation amounts fall within the range of 10–100 mm, the trunk diameter increments increase at a slower pace and tend to stabilize. The stabilized value represents the point at which the tree's tissues have reached a state of full saturation. It is important to note that different-sized trees may exhibit variations in their critical threshold values and stabilized increments.

By fitting the above relationship with a logarithmic function (as shown in Table 2), the goodness of fit, as indicated by the *R*-squared (R^2) values, is generally above 0.5. This

Table 2
Non-linear regression equation of different sample diameter increment (y) and precipitation (x)

No.	Logarithmic function formula	R^2
18	$y = 0.1082\ln(x) - 0.0731$	0.6273
82	$y = 0.0585\ln(x) - 0.0361$	0.6552
54	$y = 0.0463\ln(x) - 0.0278$	0.6351
49	$y = 0.0601\ln(x) - 0.0397$	0.5579
46	$y = 0.0681\ln(x) - 0.0318$	0.5856
48	$y = 0.0539\ln(x) - 0.0432$	0.4788

Table 3
Non-linear regression equation of different trunk diameter increment (y) in response to precipitation (x)

No.	Logistic equation	R^2
18	$y = 0.638 - 0.6223 \times \text{EXP}(-0.0199 \times x)$	$R^2 = 0.8260$
82	$y = 0.3076 - 0.3018 \times \text{EXP}(-0.026 \times x)$	$R^2 = 0.8765$
54	$y = 0.2024 - 0.2086 \times \text{EXP}(-0.0418 \times x)$	$R^2 = 0.9321$
49	$y = 0.2473 - 0.2648 \times \text{EXP}(-0.0486 \times x)$	$R^2 = 0.9477$
46	$y = 0.2984 - 0.2961 \times \text{EXP}(-0.0428 \times x)$	$R^2 = 0.9146$
48	$y = 0.2061 - 0.2318 \times \text{EXP}(-0.0533 \times x)$	$R^2 = 0.9363$

implies that the response of trunk diameter increments to precipitation follows a logarithmic pattern. Hence, the logarithmic function can be used to describe and predict the overall changes in trunk diameter increments to a certain extent. Furthermore, the variation in goodness of fit among different trees suggests that the accuracy of description and prediction may vary accordingly.

In order to seek a function that better describes the response relationship, we consider fitting the response pattern of trunk diameter increments to precipitation of 6 samples using a Logistic Regression Model, which is more consistent with biological growth curves. After model selection and parameter estimation, the final function relationship is determined and shown in Table 3.

From Table 3 it can be observed that after fitting the response of trunk diameter increments to precipitation using the Logistic Regression Model, the goodness of fit for the function relationship significantly improves. The overall R^2 value increases to above 0.8, with four trees having R^2 values exceeding 0.9. This indicates that when using the non-linear equation from Table 3 to describe and predict the trunk diameter increments caused by precipitation, a higher level of accuracy is achieved. This can be further tested and utilized in practical applications and scientific research.

3.3. Seasonal difference of trunk diameter in response to precipitation

During the course of the experiment, a total of 81 precipitation events occurred. Among these, the majority consisted of light rain (accounting for 68% of the total), with a cumulative rainfall of approximately 181 mm. The occurrence of moderate rainfall followed, accounting for 22.2% of the total, with a cumulative rainfall of approximately 167.33 mm. Lastly, the occurrence of heavy rainfall was the least frequent (accounting for 9.8% of the total), with a cumulative rainfall of approximately 411.5 mm.

Fig. 4 presents the analysis of seasonal variations in trunk diameter increments under the influence of precipitation events of similar magnitudes during the spring, summer, and autumn seasons. For each season, one instance of light rainfall (precipitation < 10 mm) and one instance of heavy rainfall (precipitation > 30 mm) were selected. The results indicate that, following precipitation events of the same magnitude, the largest increase in diameter increments occurred during the spring season. Specifically, after light and heavy rainfall, the diameter increments increased by 0.1239 and 0.3025 mm, respectively. The summer season followed closely, with diameter increments increasing by 0.0915 and 0.2914 mm after light and heavy rainfall, respectively. Conversely, the autumn season exhibited the smallest increase in diameter increments, with increments of 0.0200 and 0.2251 mm observed after light and heavy rainfall, respectively. These findings highlight that even when subjected to precipitation events of similar magnitude, the magnitude of trunk diameter increments can vary depending on the season in which they occur.

3.4. Difference of trunk diameter in response to precipitation

In order to uncover the characteristics of trunk diameter increments in relation to individual differences (diameter at breast height) induced by precipitation, this experiment analyzed the average values of trunk diameter increments

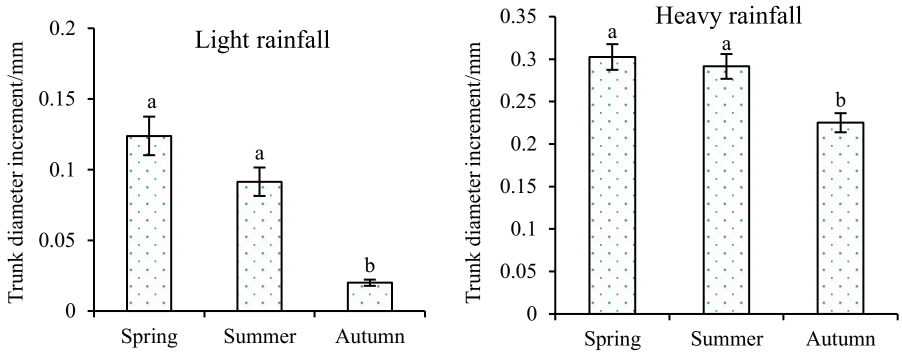

Fig. 4. Difference of trunk diameter increment in different seasons.

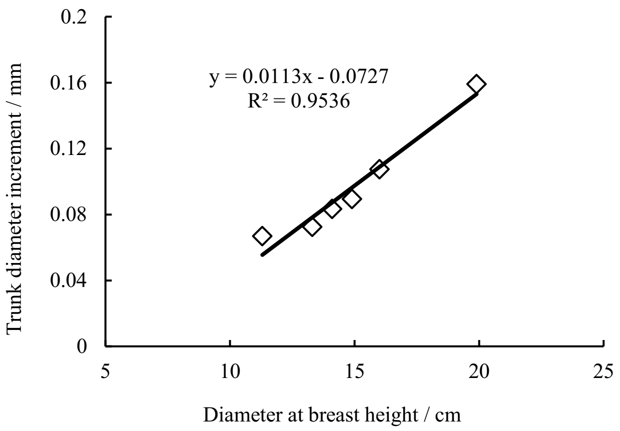

Fig. 5. Relationship between trunk diameter increment and diameter variation of sample tree.

for six different stem diameters of *P. massoniana*. Fig. 5 demonstrates that as the size of the tree (diameter at breast height denoted as x) increases, the average trunk diameter increments (y) also increase. Correlation and regression analyses reveal a highly significant positive correlation ($P < 0.01$) between the two variables. The functional relationship is described as $y = 0.0113x - 0.0727$, with an R^2 value of 0.9536, indicating a good fit. This suggests that larger individuals of *P. massoniana* exhibit a more pronounced response to precipitation, resulting in larger trunk diameter increments.

4. Discussion

The trunk radial growth pattern of *P. massoniana* within the Jigongshan National Nature Reserve exhibits distinct seasonal variations, which can be divided into three stages: rapid growth stage (May 11–July 6), slow growth stage (July 7–August 17), and stagnant growth stage (August 18–October 26). A study conducted on *Larix principis-rupprechtii*, a deciduous conifer species, at the Luya Mountain treeline in Shanxi Province, China, revealed a different pattern of trunk radial growth throughout the seasons. It was observed to consist of four stages: spring recovery of stem moisture, rapid growth in summer, dehydration and contraction in autumn, and relative stability of stem in winter. These variations can be attributed to differences in physiological characteristics of the tree species and the hydrothermal climatic conditions in different regions [11].

The present study found that precipitation is the main factor affecting the daily variation of trunk diameter in *P. massoniana* within the nature reserve, which is consistent with the conclusions of most previous studies [3,6]. Other studies have indicated that soil temperature is the primary factor influencing radial growth in *P. massoniana* in Jiangxi Province, China, suggesting that the factors influencing trunk radial growth may vary in different regions [15,19]. Additionally, the response of trunk radial growth to temperature can vary greatly for the same tree species in different elevations, which is closely related to local habitat conditions [20].

Due to differences in biological characteristics of trees, meteorological factors, site conditions, and silvicultural practices, there are evident variations in daily trunk diameter increments among different individuals of *P. massoniana* [3,15,21]. While the seasonal trends of trunk radial growth are consistent among the six sample trees in this study, the trunk diameter increments differ between individual trees, which may be attributed to differences in tree characteristics and stem tissue activity [22,23]. Through simulating the trunk diameter increments of the six *P. massoniana* trees with different stem diameters, it can be observed that as the stem diameter increases, the trunk diameter increment also increases, indicating a trend of "the strong get stronger". Research has shown that different-sized *P. massoniana* trees have a significant impact on cumulative diameter growth during the growing season, with the order of influence from high to low being diameter at breast height > tree height > crown thickness > branch height, where diameter at breast height and tree height have a greater impact on diameter growth than crown characteristics [3,6,24]. Therefore, within the same stand and age of *P. massoniana*, the differences in trunk diameter increments among trees are related to their dominance, with larger differences in trunk diameter increments observed for trees with greater dominance.

This study indicated a positive correlation between daily trunk radial increment of *P. massoniana* and precipitation. A study on the trunk growth of *Pseudotsuga menziesii* in central British Columbia, Canada, also found a significant positive correlation between trunk radial growth and precipitation in that region [25]. Furthermore, as the study area is located within the Jigongshan National Nature Reserve and the soil is relatively poor, it is susceptible to drought conditions. Thus, water availability becomes a major limiting factor for the growth of *P. massoniana*, making precipitation have a significant impact on trunk radial growth.

Based on a study examining the radial variations in the trunks of five tree species in the tropical dry forests of southern Ecuador, it was determined that the growth of the xylem is primarily constrained by precipitation levels [26]. This finding underscores the significant influence that precipitation exerts on the radial growth of trees. Furthermore, an investigation conducted by Hu and Fan [27] on four tree species in tropical karst forests revealed that precipitation is the primary limiting factor for radial growth, particularly during the early stages of growth.

Existing research has indicated a positive correlation between precipitation levels during the growing season and the radial growth of trees [28]. However, there are evident individual differences in the response of trunk radial growth to meteorological factors [29–31]. These differences can be attributed to variations among tree individuals and multiple influencing factors, necessitating further research. Studies on plants such as *Citrus limon*, *Canarium album*, *R. pseudoacacia*, and *Quercus liaotungensis* have shown that the daily radial variations in trunk diameter can better reflect the water status of the tree compared to other water-related physiological indicators [32,33]. Therefore, in this study, quantitative analysis of the characteristics of trunk diameter increments in response to precipitation was conducted to explore the impact of inherent water use efficiency on the growth of *P. massoniana*, which can provide a theoretical basis for vegetation establishment in the northern distribution boundary of *P. massoniana*.

5. Conclusions

- The increment in trunk diameter of *P. massoniana* exhibits a pattern of rapid increase followed by slower growth and eventually reaching a stable state as precipitation increases. The critical threshold and final stable values differ among trees of different sizes. The relationship between trunk diameter increment (y_1) and precipitation (x_1) can be described and predicted using a Logistic Regression Model $y_1 = a - b \times \text{EXP}(c \times x_1)$, which shows a good fit.
- For precipitation events of the same level, the response of trunk diameter increment varies as follows: spring > summer > autumn.
- There is a significant positive correlation ($P < 0.01$) between tree size (diameter at breast height, x_2) and trunk diameter increment (y_2). The linear relationship between the two variables is expressed as $y_2 = 0.0113x_2 - 0.0727$ ($R^2 = 0.9536$).

In summary, it can be concluded that precipitation effectively promotes the increment in trunk diameter of *P. massoniana*. The magnitude of this increment increases with higher precipitation levels, exhibiting a non-linear pattern of rapid growth followed by slower growth and eventually reaching a stable state. Furthermore, the increment in trunk diameter induced by precipitation is also influenced by the size of the tree, with larger trees showing greater increments.

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