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Radial Variation and Early Prediction of Wood Properties in *Pinus elliottii* Engelm. Plantation

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Abstract: To explore the radial variation in wood properties of slash pine (*Pinus elliottii* Engelm.) during its growth process and to achieve the early prediction of these properties, our study was carried out in three slash pine harvest-age plantations in Ganzhou, Jian, and Jingdezhen, Jiangxi province of South China. Wood core samples were collected from 360 sample trees from the three plantations. SilviScan technology was utilized to acquire wood property parameters, such as tangential fiber widths (TFWs), radial fiber widths (RFWs), fiber wall thickness (FWT), fiber coarseness (FC), microfibril angle (MFA), modulus of elasticity (MOE), wood density (WD) and ring width (RD). Subsequent systematic analysis focused on the phenotypic and radial variation patterns of wood properties, aiming to establish a clear boundary between juvenile and mature wood. Based on determining the boundary between juvenile and mature wood, a regression equation was used to establish the relationship between the properties of juvenile wood and the ring ages. This relationship was then extended to the mature wood section to predict the properties of mature wood. Our results indicated significant differences in wood properties across different locations. The coefficients of variation for RD and MOE were higher than other properties, suggesting a significant potential for selective breeding. Distinct radial variation patterns in wood properties from the pith to the bark were observed. The boundary between juvenile and mature wood was reached at the age of 22. The prediction models developed for each wood property showed high accuracy, with determination coefficients exceeding 0.87. Additionally, the relative and standard errors between the measured and predicted values were kept below 10.15%, indicating robust predictability. Mature wood exhibited greater strength compared to juvenile wood. The approach of using juvenile wood properties to predict those of mature wood is validated. This method provides a feasible avenue for the early prediction of wood properties in slash pine.

Keywords: *Pinus elliottii* Engelm.; radial variation; early prediction; wood properties; juvenile wood; mature wood

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1. Introduction

Radial variation is a term used to describe changes in wood properties along the radius or annual rings. It plays a crucial role in understanding the variability of wood properties during tree growth and is essential for distinguishing between juvenile and mature wood. The radial variation patterns of wood properties are highly significant for early prediction of wood properties, as well as for determining the optimal logging period and improving wood quality [1–3]. Juvenile wood, known as "immature wood", forms a cylindrical structure surrounding the pith and is a unique component developed during early tree growth. Juvenile wood has low rigidity and strength, rendering it susceptible to bending and deformation when exposed to external forces. In contrast, mature wood possesses greater strength and rigidity, effectively resisting external forces. Research has shown that by examining the variation in juvenile wood properties, it is possible to predict the properties of mature wood to achieve early assessment of wood quality, thereby facilitating the improvement of timber quality [4–6]. However, the transition from juvenile to mature wood is a gradual process without distinct boundaries. This is particularly true for conifer species, where a noticeable transition period exists between juvenile and mature wood, which complicates the prediction of mature wood properties based on juvenile wood [7,8]. Additionally, the boundaries separating juvenile and mature wood can vary significantly based on wood properties, growth rate, individual differences, and environmental conditions [9]. Researchers worldwide have conducted extensive studies utilizing indicators like microfibril angle, growth ring width, and basic density to delineate juvenile and mature wood. Studies have identified that in artificial forests of Japanese red pine (*Pinus densiflora* Sieb. et Zucc.) [10], Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.) [11], Korean pine (*Pinus koraiensis* Siebold et Zuccarini) [7], and Jack pine (*Pinus banksiana* Lambert) [12], the boundaries occur at age 12, age 14, age 15, and age 18, respectively. Based on the radial variation pattern of different wood properties, prediction equations for mature wood properties have been developed, enabling early assessment of wood quality for these species, thereby establishing a solid foundation for early selection and oriented cultivation of wood properties.

The wood quality directly impacts the yield and quality of pulp, paper and sawn timber products. Notably, the anatomical properties of wood, encompassing the microfibril angle, fiber diameter, and fiber wall thickness, significantly influence the fiber composites' performance, textile strength, and paper tear resistance [13]. Furthermore, the wood physical–mechanical properties, including wood density and elastic modulus, serve as vital indicators for evaluating wood strength and its resistance to compression deformation [14,15]. Improving wood quality involves not only enhancing the average level of wood properties but also reducing the variability in wood properties. Zobel et al. [16] highlighted that by reducing the juvenile phase of tree growth, the presence of juvenile wood can be diminished or modified, and the extent of wood property variation from pith to bark can be altered, thereby minimizing disparities in wood properties between juvenile and mature wood and enhancing wood utilization.

Slash pine (*Pinus elliottii* Engelm.) is a successfully introduced conifer species within the subtropical regions of China [17,18]. This species is known for its high growth rate, straight trunks, and superior wood quality, meaning it is extensively utilized in sectors including papermaking, the construction industry, and furniture manufacturing [19]. As plantation forests undergo oriented cultivation and intensive management, there has been an increasing focus on the improvement of wood properties. However, previous improvement efforts for slash pine have predominantly prioritized growth traits and resin production, and progress in enhancing the wood properties of slash pine has been relatively sluggish [20].

To address the disconnect between the oriented cultivation of slash pine plantations and wood processing utilization, early prediction of wood properties has gradually become one of the central issues in the research field of slash pine plantation cultivation. Predicting mature wood properties is based on the radial variation patterns of different wood properties. After determining the boundary between juvenile and mature wood, the best regression models for various wood properties of juvenile wood in relation to the age of growth rings are selected through statistical regression analysis. These regression models are then extrapolated to the mature wood section, resulting in predicted values for mature wood. By comparing these predicted values to the actual measurements, which show a relatively small relative error, the results are considered quite satisfactory. Through the accurate early prediction of wood properties in mature wood, a comprehensive understanding of the wood quality can be rapidly gained, facilitating a timely assessment of the influence of cultivation measures on wood properties of slash pine, holding substantial practical value in improving wood utilization, and reducing the rotation cutting period [21–23].

In this study, SilviScan technology was employed to obtain the growth ring parameters of wood properties of 360 sample trees from three slash pine plantations. The detailed aims of this research were (1) to examine the phenotypic and radial variation patterns for different wood properties; (2) to determine the boundary between juvenile and mature wood and to ascertain the differences between juvenile and mature wood; (3) to establish early prediction models for various wood properties.

2. Materials and Methods

2.1. Study Material

The test plantations are in Jingdezhen, Ji'an, and Ganzhou in Jiangxi Province, South China (Table 1). These sites are characterized by a subtropical monsoon humid climate, with mild weather, ample precipitation, and red soil. Each test plantation consisting of 112 slash pine families imported from the United States. A completely randomized block design with five replications each consisting of four-tree-row plots was applied in all three test plantations. Seedling cultivation commenced in the spring of 1989, followed by afforestation in the spring of 1990. In 2018, the same 20 families were selected from the 112 in all three plantations for the study. In each test plantation, within the first, third, and fifth blocks, two sample trees were randomly chosen from each family, resulting in 360 sample trees that were selected from the three plantations.

From each sample tree, a single increment core, 12 mm in thickness and extending from the bark to the pith, was extracted at breast height (Figure 1). In total, 360 cores were acquired. The SilviScan technology (CSIRO, Canberra, Australia) facilitated the assessment of variations from bark to pith, recording modulus of elasticity (MOE) and microfibril angle (MFA) values as average readings across 5 mm radial intervals, while those of radial fiber widths (RFWs), tangential fiber widths (TFWs), fiber wall thickness (FWT), fiber coarseness (FC) and wood density (WD) were measured for 25 µm intervals [24,25]. The calculation method of the MOE is MOE = 0.14 $(I_{CV}\text{WD})^{0.85}$, where I_{CV} is the diffraction intensity of X-rays when measuring the MFA. Upon completion of the measuring, each wood core was subjected to dendrochronological dating, with the width of each growth ring being measured [26,27]. And thus, growth ring values for each wood property were acquired. The analysis was confined to the age range of 4–27 years. This limitation was necessitated by the absence of annual rings in some samples proximal to the pith.

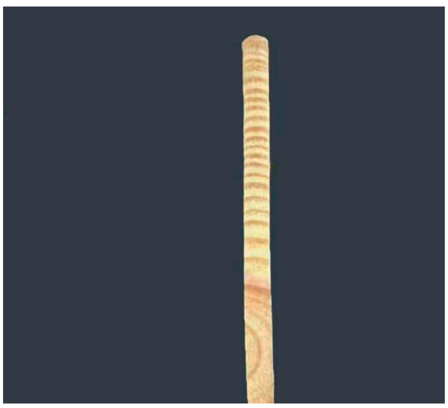

Figure 1. The wood increment of slash pine.

Table 1. Basic information of the three test sites.

Test Site	Longitude W (°)	Latitude N (°)	Altitude (m)	Mean Annual T (°C)	Rainfall (mm/Year)
Jingdezhen	117.25	29.37	80	17.2	1805
Jian	115.13	27.22	90	18.3	1487
Ganzhou	114.93	25.38	250	20.2	1318

2.2. Statistical Analyses

Student's t-test and Tukey's mean separation test (p = 0.05) were used to determine the statistical significance of differences.

The process of using the ordered clustering optimal partitioning method to classify the samples and determine the boundary between juvenile wood and mature wood is as follows. Assume there are n samples, each with m observations, represented by an observation vector $\{x_1, x_2, \cdots, x_n\}$. If naturally arranged in sequence, there are $n-1$ natural partition points. If we want to divide n samples into k categories, there are a total of C_{n-1}^{k-1} ways of division according to the combination principle. In order to find the optimal partition among them, the class diameter should be first defined. Assume that in a certain partition, the r class has $\{x_{i_r}, x_{i_{r+1}}, \cdots, x_{j_{r-1}}, x_{j_r}\}$ samples, with $n_r = j_r - i_r + 1$; the sum of the squares of the deviations for that class is defined as the class diameter $D(i_r, j_r)$. The sum of the class diameters of all k classes is defined as the classification objective function $e[p(n,k)]$.

$$D(i_r, j_r) = \sum_{t=i_r}^{j_r} \left(x_i - \frac{1}{n_r} \sum_{t=i}^{j} x_i \right)^r \left(x_i - \frac{1}{n} \sum_{t=i}^{j} x_i \right)$$

$$e[p(n,k)] = \sum_{r=i}^{k} D(i_r,\ j_r)$$

We can calculate the objective function values for all C_{n-1}^{k-1} ways of partitioning, and the partitioning corresponding to the minimum value of the objective function is called the optimal partition. The ordered clustering optimal partitioning method was implemented in the SPSS statistics software (Version 27, IBM SPSS Inc., Chicago, IL, USA).

According to the results of the ordered clustering optimal partitioning method, the boundary between juvenile wood and mature wood is determined. Then, based on the method of regression analysis, the measured values of the juvenile wood are used to predict the mature wood [28]. The analysis process is as follows: first, construct the regression equation that best fits the change in wood properties with age. Next, establish the equation for the variation in juvenile wood measured values with ring age, which is the prediction equation. This prediction equation can be extended to the mature wood section to obtain predicted values for various properties of mature wood. Then, compare the predicted values with the measured values in the mature wood and use the mean relative error and the mean standard error to indicate their accuracy. The formulas for the regression model and error calculation are as follows:

$$y = a \pm be^x$$

$$E = \frac{y_i - \hat{y}_i}{ny_i}$$

$$SE = \sqrt{\frac{\sum E_i^2}{n}}$$

where E represents the mean relative error, y_i represents the measured value, $\hat{y}_i$ represents the predicted value, n is the number of samples, and SE represents the mean standard error. The method of regression analysis was implemented in the OriginPro software (Version 2021, OriginLab Corporation, Northampton, MA, USA).

3. Results

3.1. Phenotypic and Radical Variation in Wood Properties

A multiple comparison method was employed to analyze the phenotypic variation in wood properties of slash pine at the following three sites: Jingdezhen, Ji'an, and Ganzhou. Inspection of Figure 2 revealed that all the wood properties exhibited significant differences between different sites. Among all the wood properties, ring width and MOE demonstrated the highest coefficients of variation for joint sites, with 24.01% and 21.74%, respectively (Figure 3).

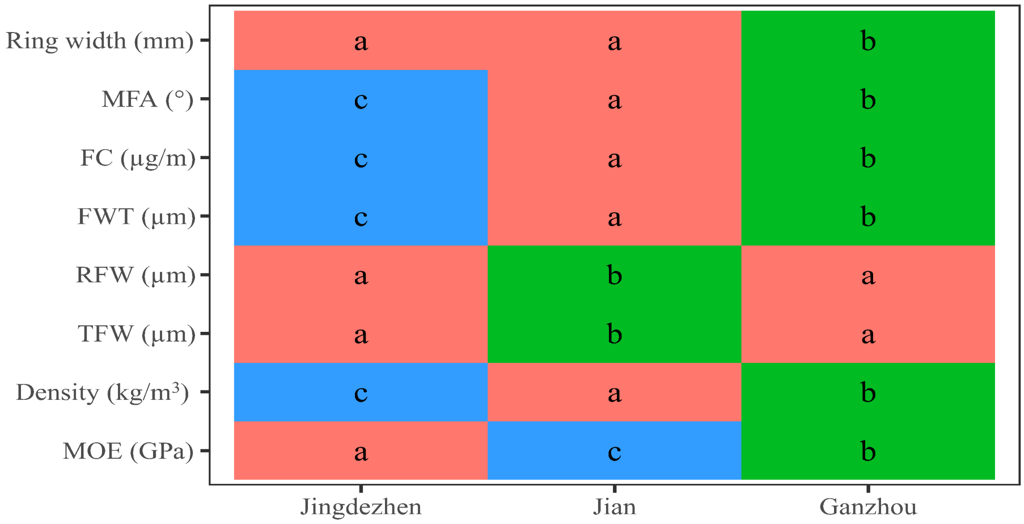

Figure 2. Multiple comparison results for the wood properties for all three sites. MFA, microfibrillar angle; FC, fiber coarseness; FWT, fiber wall thickness; TFW, tangential fiber widths, RFW, radial fiber widths; MOE, modulus of elasticity. Different lowercase letters (a, b, c) indicate significant differences with Tukey's test ($p < 0.05$).

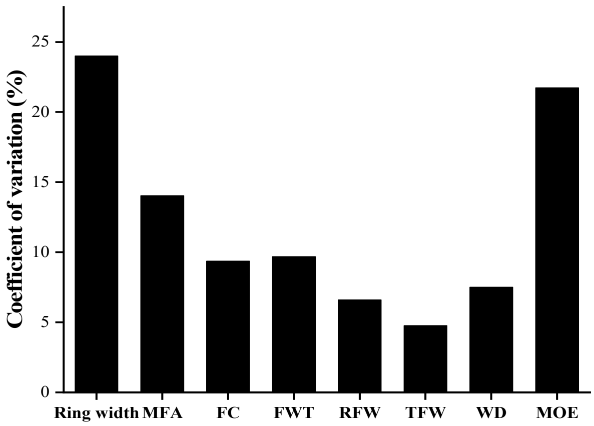

Figure 3. Coefficients of variation for the wood properties for joint sites. MFA, microfibrillar angle; FC, fiber coarseness; FWT, fiber wall thickness; TFW, tangential fiber widths, RFW, radial fiber widths; WD, wood density; MOE, modulus of elasticity.

The age trends of annual wood properties from cambial ages 4 to 27 for joint sites were presented in Figure 4. Ring width and MFA were characterized by a rapid decrease before the ages 12–13 (Figure 4A,B). After ages 12–13, the trend of ring width decreased gradually overall, while the MFA was stabilized. Fiber coarseness, TFW and MOE underwent a rapid increase before the ages 13–14, followed by a reduced growth rate after that (Figure 4C,F,H). Overall, FWT and wood density exhibited a gradual increase from the pith to the outer wood as the tree ages with some fluctuations (Figure 4D,G). The radial variation pattern of RFW was not obvious (Figure 4E).

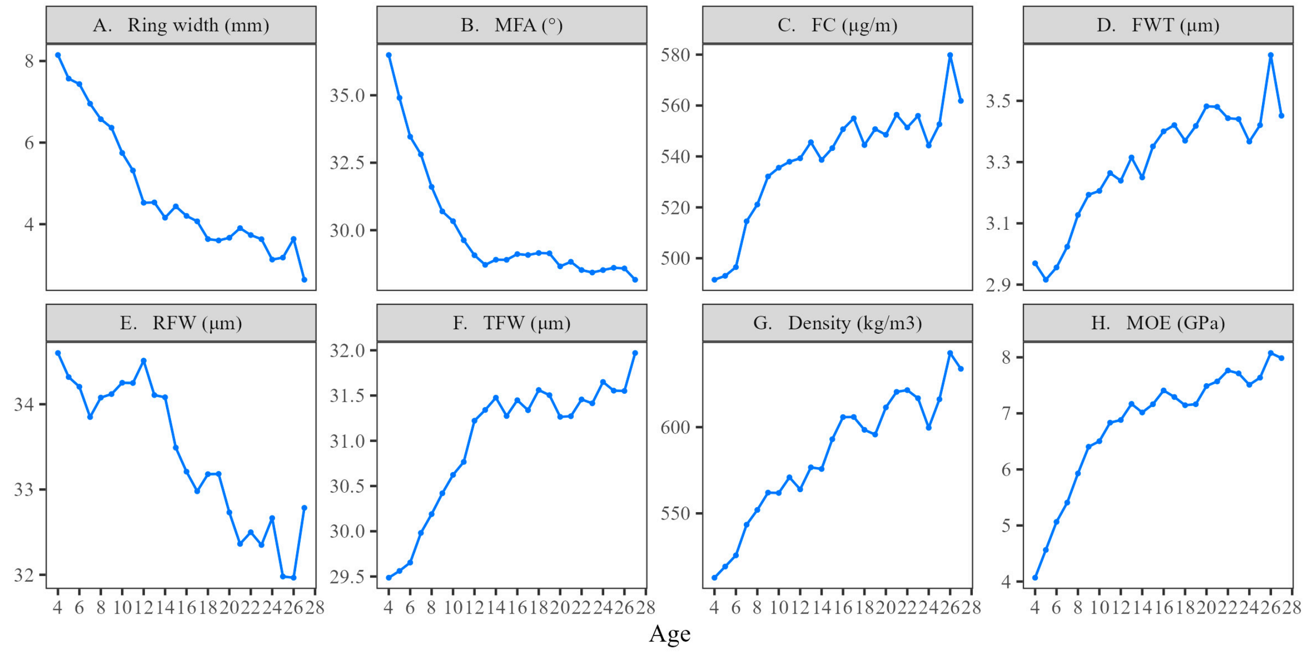

Figure 4. Age trends of annual ring wood properties from cambial ages 4 to 27 for joint sites. (**A**) Ring width. (**B**) MFA (microfibrillar angle). (**C**) FC (fiber coarseness). (**D**) FWT (fiber wall thickness). (**E**) Radial fiber widths (RFW). (**F**) Tangential fiber widths (TFW). (**G**) Wood density. (**H**) MOE (modulus of elasticity).

3.2. Demarcation between Juvenile and Mature Wood

The juvenile, transitional, and mature phases of various wood properties in slash pine were classified using the ordered clustering optimal partitioning method. Table 2 presents the following chronological order of various wood properties maturity across the three sites: MOE, MFA, RW, WD, FWT, TFW, FC, and RFW, corresponding to the age 14, age 15, age 18, age 19, age 20, age 20, age 22, and age 22, respectively. Across the three sites, FC and RFW in Jingdezhen exhibited the latest maturity, reaching it at age 22. On the whole, the age 22 was identified as the boundary point between juvenile and mature wood in slash pine, and it could be considered juvenile wood before the age 22.

Table 2. Juvenile, transitional, and mature period of wood properties of slash pine for the three sites.

Trait (Site)	Jingdezhen			Jian			Ganzhou		
	Juvenile Period	Transitional Period	Mature Period	Juvenile Period	Transitional Period	Mature Period	Juvenile Period	Transitional Period	Mature Period
Ring width/year	4–7	8–17	18–27	4–6	7–11	12–27	4–6	7–11	12–27
MFA/year	4–7	8–14	15–27	4–8	9–13	14–27	4–5	6–13	14–27
FC/year	4–8	9–21	22–27	4–8	9–19	20–27	4–7	8–19	20–27
FWT/year	4–6	7–19	20–27	4–10	11–15	16–27	4–7	8–15	16–27
RFW/year	4–16	17–21	22–27	4–13	14–18	19–27	4–6	7–15	16–27
TFW/year	4–11	12–19	20–27	4–8	9–15	16–27	4–9	10–19	20–27
WD/year	4–6	7–18	19–27	4–7	8–13	14–27	4–6	7–15	16–27
MOE/year	4–7	8–13	14–27	4–7	8–13	14–27	4–5	6–12	13–27

MFA, microfibrillar angle; FC, fiber coarseness; FWT, fiber wall thickness; TFW, tangential fiber widths, RFW, radial fiber widths; WD, wood density; MOE, modulus of elasticity.

The differences between juvenile and mature wood were significant for all wood properties in slash pine for the joint sites (Table 3). Specifically, mature wood exhibited higher values of BD, MOE, FC, FWT, and TFW compared to juvenile wood. Conversely, mature wood demonstrated lower values of RW, MFA, and RFW in comparison to juvenile wood. Moreover, significant differences between juvenile and mature wood for most wood properties at each site were also observed in the present study (Table 3).

Table 3. Mean values and standard error of the mean (SE) for juvenile and mature wood of wood properties of slash pine for all three single and joint sites.

	Wood (Trait)	RD/mm		MFA/°		FC/μg·m^{-1}		FWT/μm		RFW/μm		TFW/μm		WD/kg·m^{-3}		MOE/GPa	
		Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Joint sites	Juvenile wood	5.19	0.07	30.42	0.22	533.77	2.73	3.26	0.02	33.68	0.13	30.84	0.08	574.53	2.42	6.571	0.08
	Mature wood	3.24	0.08	28.46	0.27	558.86	4.23	3.43	0.02	32.59	0.15	31.62	0.13	621.86	2.62	7.772	0.09
	F value	4.13 *		5.46 *		26.92 **		22.71 **		7.55 **		33.67 **		4.41 *		15.02 **	
Jingdezhen	Juvenile wood	5.14	0.12	28.66	0.39	519.23	4.37	3.07	0.03	35.04	0.20	31.44	0.16	542.13	3.46	6.78	0.13
	Mature wood	3.46	0.17	26.66	0.46	530.80	6.70	3.18	0.04	32.95	0.25	31.62	0.25	598.20	4.43	7.92	0.16
	F value	16.84 **		3.92 *		23.35 **		24.69 *		4.10 *		9.89 **		7.48 **		4.01 *	
Jian	Juvenile wood	5.20	0.14	32.25	0.39	548.32	5.60	3.45	0.03	32.32	0.22	30.24	0.12	607.70	4.02	6.34	0.17
	Mature wood	3.16	0.11	30.01	0.51	586.94	8.61	3.68	0.04	32.24	0.32	31.63	0.22	642.63	4.78	7.67	0.20
	F value	1.42		6.41 *		5.99 *		4.09 *		21.01 **		23.18 **		6.02 *		10.03 **	
Ganzhou	Juvenile wood	5.23	0.10	30.356	0.305	533.77	3.68	3.26	0.02	33.68	0.15	30.84	0.10	573.77	2.64	6.59	0.11
	Mature wood	3.12	0.10	28.714	0.360	558.87	5.47	3.43	0.03	32.60	0.20	31.63	0.16	624.77	3.35	7.73	0.13
	F value	0.44		1.78		5.75 *		6.89 **		4.52 *		13.21 **		7.58 *		3.97 *	

RD, ring width; MFA, microfibrillar angle; FC, fiber coarseness; FWT, fiber wall thickness; TFW, tangential fiber widths, RFW, radial fiber widths; WD, wood density; MOE, modulus of elasticity. ** $p < 0.01$, * $0.01 < p < 0.05$, level of significance of effects.

3.3. Early Prediction of Wood Properties

The wood properties can be analyzed in the early stages using regression analysis (except for RFW). By extending the prediction equation established based on the measured values of various wood properties during the first 21 years of juvenile wood to mature wood, it is possible to obtain predicted values for the various wood properties of the mature wood. This allows for determining the goodness of fit of the prediction equation by comparing the predicted values with the measured values in mature wood (Figure 5). The determination coefficients of the regression equations, simulated for different wood properties, are all greater than 0.77, while the determination coefficients of the prediction equations are all greater than 0.87 (Table 4). The range of the relative error distribution between the measured values and predicted values is 0.55% to 8.64%, and the range of the standard error distribution is 0.82% to 10.15%. Thus, it can be concluded that all wood properties show a favorable level of predictability, with MFA and TFW exhibiting the most minor relative and standard errors, resulting in the best goodness of fit for the prediction equation.

Table 4. Regression and prediction model of wood properties of slash pine.

Trait	Regression Equation	Prediction Equation	Mean Relative Error/%	Mean Standard Error/%
Ring width	$y = 2.67 + 7.92 \times e^{-0.11\,a}$ ($R^2 = 0.97$)	$y = 2.51 + 8.90 \times e^{-0.11\,a}$ ($R^2 = 0.97$)	8.64	10.15
Microfibrillar angle	$y = 28.51 + 17.68 \times e^{-0.26\,a}$ ($R^2 = 0.98$)	$y = 28.61 + 23.58 \times e^{-0.27\,a}$ ($R^2 = 0.98$)	0.65	0.83
Fiber coarseness	$y = 562.48 - 105.38 \times e^{-0.13\,a}$ ($R^2 = 0.80$)	$y = 557.20 - 127.69 \times e^{-0.16\,a}$ ($R^2 = 0.89$)	2.03	2.75
Fiber wall thickness	$y = 3.50 - 0.76 \times e^{-0.11\,a}$ ($R^2 = 0.77$)	$y = 3.54 - 0.85 \times e^{-0.10\,a}$ ($R^2 = 0.87$)	2.76	3.63
Tangential fiber width	$y = 31.73 - 3.57 \times e^{-0.14\,a}$ ($R^2 = 0.88$)	$y = 31.68 - 4.22 \times e^{-0.15\,a}$ ($R^2 = 0.88$)	0.55	0.82
Wood density	$y = 660.21 - 180.66 \times e^{-0.07\,a}$ ($R^2 = 0.94$)	$y = 663.37 - 196.58 \times e^{-0.07\,a}$ ($R^2 = 0.96$)	1.59	2.05
Modulus of elasticity	$y = 7.80 - 6.32 \times e^{-0.17\,a}$ ($R^2 = 0.97$)	$y = 7.56 - 8.23 \times e^{-0.21\,a}$ ($R^2 = 0.98$)	3.68	4.27

a represents age.

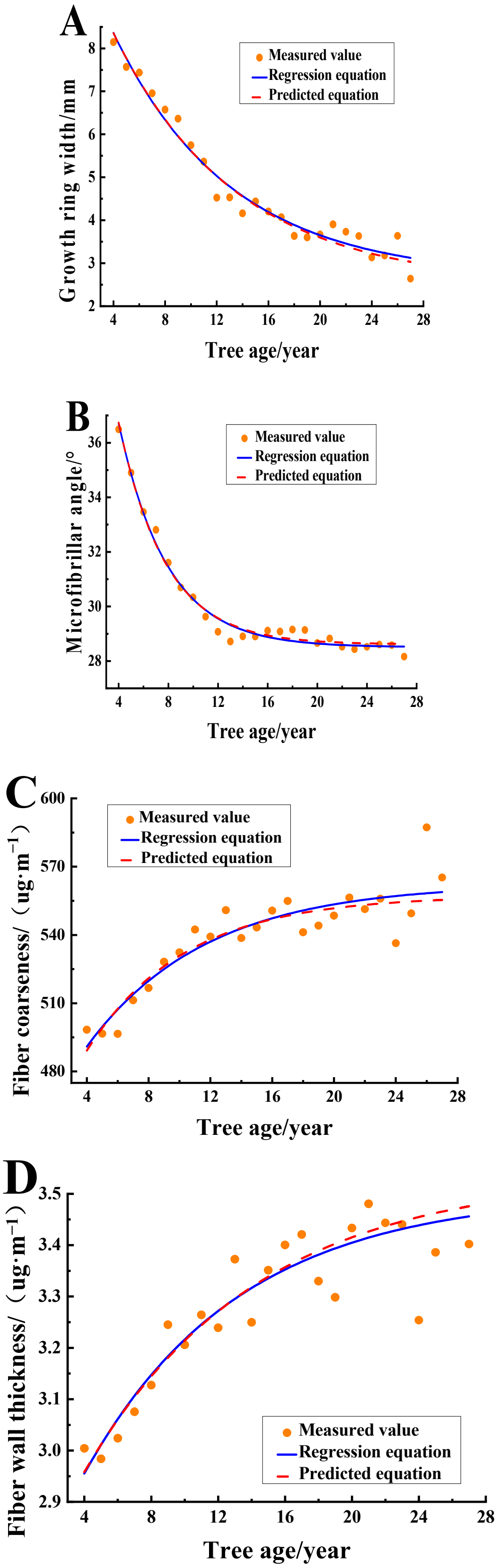

Figure 5. *Cont.*

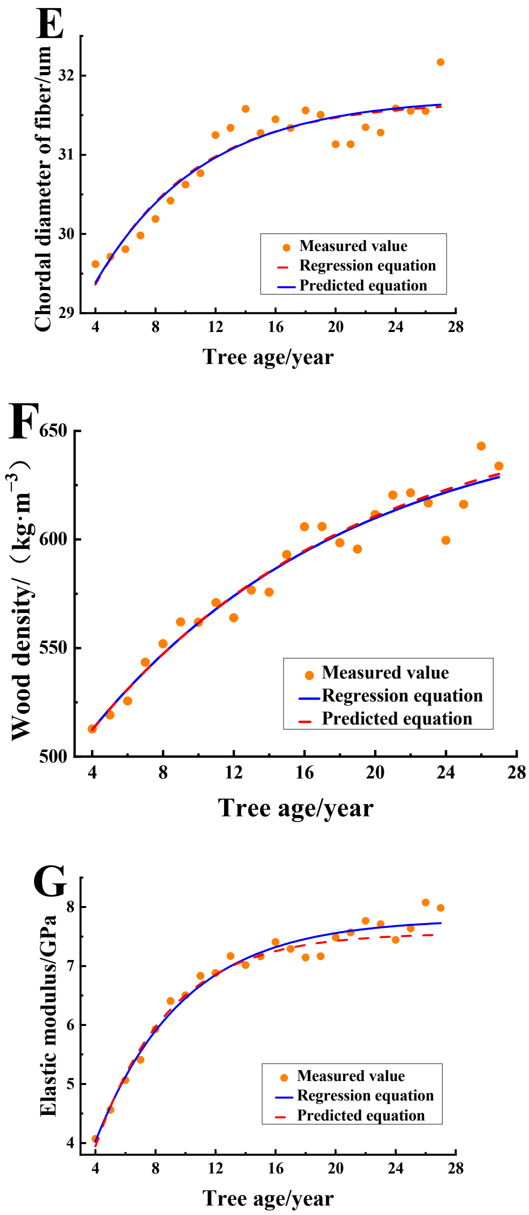

Figure 5. Relationship between tree age and wood properties. (**A**) Ring width. (**B**) Microfibrillar angle. (**C**) Fiber coarseness. (**D**) Fiber wall thickness. (**E**) Tangential fiber width. (**F**) Wood density. (**G**) Modulus of elasticity.

4. Discussion

The early prediction of wood properties holds significant scientific importance for the cultivation of high-quality slash pine [29,30]. This study identified the boundary point between juvenile and mature wood and established early prediction models for mature wood based on a systematic analysis of the phenotypic variation and radial variation patterns of the main wood properties of slash pine. The analysis of phenotypic variation revealed that among the different wood properties, RW and MOE exhibited the highest coefficient of variation for joint sites, indicating that the selection potential for these two traits was larger than that for other wood properties in this study. Significant differences between different sites were observed for all wood properties. These differences might reflect differences in the plant environment, or the influence of climate variables [31].

The wood properties of slash pine displayed evident radial variation between growth rings. Specifically, there was a rapid decrease in RW and MFA from the pith to the age of 12–13 years. Overall, FC, FWT, TFW, WD and MOE fluctuated and increased with aging, conforming to the second type defined by Pashin and Zeeuw [32], termed the "fluctuating and increasing type". Microfibril angle refers to the angle formed between the arrangement direction of microfibrils in the secondary wall S2 layer of the cell wall and the cell's main axis direction. It serves as an essential factor in determining wood hardness and strength. Generally, wood strength properties such as BD and MOE are believed to correlate negatively with MFA [33,34]. In our study, as tree age increased, MFA showed a decreasing radial variation pattern, while BD and MOE demonstrated an increasing radial variation pattern, validating the results above. The radial variation patterns of wood density differ significantly among various tree species. Pashin and Zeeuw [32] summarized the following three types of radial variation patterns in wood density: Type I, the asymptotically increasing type, which displays continuous linear or curved growth from the pith to the outer layers, gradually decreasing near the bark; Type II, the fluctuating and increasing type, characterized by fluctuations with a gradual increase from the pith to the outer layers; and Type III, the fluctuating and shifting type, which exhibits a straight or curved decrease from the pith to the outer layers. Pine species such as hoop pine (*Araucaria cunninghamii* Sweet) and radiata pine (*Pinus radiata* D. Don) illustrate a decreasing trend in wood density from the pith to the bark, conforming to Panshin's Type III, which contrasts entirely with slash pine (classified as Type II according to Panshin) [35–37]. Some other pine species manifest multiple types of radial variation patterns in wood density. For instance, ponderosa pine (*Pinus ponderosa* Douglas ex C. Lawson) shows three types. The underlying cause of the diverse types of radial variation in wood density lies in the changes in tracheid diameter, cell wall thickness, the proportion of earlywood and latewood, the number of ray cells, and the content of extractives [5].

The formation of juvenile wood results from the prolonged impact exerted by the apical meristem, an active region in the tree's crown, on the cambium layer of wood [38,39]. As the tree's crown continues to ascend during its growth process, the influence of the apical meristem on the cambium layer of wood gradually diminishes, leading to the development of mature wood. This process signifies the transformation of juvenile wood into mature wood, which occurs through the gradual accumulation of quantitative changes, ultimately culminating in a qualitative leap. The distinction between juvenile wood and mature wood often fluctuates based on variations in wood properties, growth rate, individual distinctions, and site conditions. For instance, considering properties such as the microfibril angle, fiber length, and wood density, the transition from juvenile to mature wood in Korean pine was discerned at the respective time points of the age 10, age 12, and age 17 [7,40]. In the present study, if one solely employed wood density as the criterion while considering factors from multiple sites simultaneously, the distinction between juvenile and mature wood in slash pine could be established at the age of 19 years. Alternatively, other properties indicated that the boundaries could be established at the age 14 for MOE, the age 15 for MFA, the age 18 for RW, the age 20 for FWT, the age 20 for TFW, the age 22 for FC, and the age 22 for RFW. It is important to note that the maturity of a single wood property does not adequately represent the overall quality of the wood. Only when all wood properties have matured can superior wood quality be attained. Consequently, after comprehensive analysis, it was determined that the boundary separating juvenile and mature wood in slash pine occurred in the 22nd year of tree growth.

Many studies have shown that the mature wood of hardwood species has better wood quality than juvenile wood. The mature wood has typical wood quality of the tree species, while the juvenile wood has lower structural and physical features than the mature wood of the same tree [41,42]. In this study, there were significant differences in various wood properties between juvenile and mature wood of slash pine, and the radial variation curve of wood properties for mature wood was more stable with more minor fluctuations. Additionally, the mature wood had lower mean MFA values compared to the juvenile wood, while wood strength properties such as BD and MOE were higher in mature wood than in juvenile wood. This indicates that the mature wood of slash pine exhibits better wood quality, consistent with the above-mentioned research results. The content of mature wood often determines the wood quality, and accurate prediction of wood properties of mature wood is of great significance for the efficient utilization of wood [43]. In this study, using regression analysis, prediction equations were established based on the measured values of various wood properties over the previous 21 years, with determination coefficients greater than 0.87. The theoretical predicted values of wood properties for mature wood obtained from the prediction equations were close to the measured values, with relative errors and standard errors less than 10.15%, indicating that using juvenile wood properties to predict those of mature wood and achieve early prediction of slash pine wood quality is feasible.

5. Conclusions

This study utilized the SilviScan technique to acquire annual ring parameter values for the primary wood properties of 360 sample trees from three slash pine plantations. The research systematically explored the phenotypic and radial variation patterns of different wood properties, which served as the basis for distinguishing between juvenile and mature wood. To predict the wood properties of mature wood, this study utilized juvenile wood and established early prediction models for various wood properties. The main findings can be summarized as follows:

(1) Slash pine exhibited significant differences between different sites in various wood properties.
(2) Noticeable radial variation patterns existed between growth rings. Moving from the pith to the bark, RW and MFA exhibited a rapid decrease. Conversely, FC, FWT, TFW, WD, and MOE demonstrate an overall fluctuating increasing trend.
(3) The boundary between juvenile and mature wood was reached at the age of 22. Mature wood exhibited higher wood strength than juvenile wood.
(4) The established early prediction models for various wood properties displayed determination coefficients surpassing 0.87. Furthermore, the relative and standard errors between measured and predicted values are minimal, indicating high predictability.

Slash pine is a representative fast-growing tree species and exhibits a high proportion of juvenile wood in artificial forests, which leads to significant variations in wood properties, greatly affecting the wood quality and potential applications. The practical significance of this research is that it provides a feasible early prediction method for the wood properties of slash pine plantations, thereby facilitating the optimization of forestry resource management and utilization. In the future, further refinement and application of this prediction model could significantly support improvements in wood quality and forestry production efficiency. Additionally, it provides a scientific basis for the genetic improvement and sustainable management of slash pine.

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