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Disturbance and Growth: Deciphering the Impact of Resin Tapping on Biomass Allocation and Allometric Growth Patterns in *Pinus massoniana*

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ABSTRACT: China has long been the world's largest producer of pine resin. Pinus massoniana Lamb. It is a significant afforestation and timber species in southern China, accounting for more than half of the forest stock in southern China， It proliferates, with high resin yield, making it an essential component of forestry operations south of mountainous areas and a pillar industry in forestry. However, studies on the impact of resin tapping on biomass allocation and height-diameter allometric growth dynamics of *Pinus massoniana* are unclear. This study focused on *Pinus massoniana* plantations in the South Subtropical Region of Guangxi to explore the effects of resin tapping on biomass allocation patterns and allometric growth relationships. Whole-tree harvesting was used to collect samples, with diameter at breast height, tree height, and ground diameter as essential variables to construct allometric biomass models suitable for *Pinus massoniana* forests under resin tapping disturbance. We constructed allometric growth models for aboveground and belowground parts and between organs to reveal the best biomass models and predictive variables. The results showed that resin tapping disturbance significantly reduced the biomass of various organs in *Pinus massoniana*, with reductions in stem, bark, root, aboveground, and total biomass statistically significant (P<0.05). However, the changes in leaf and branch biomass were insignificant (P>0.05), indicating that the impact of resin tapping is selective among different organs. The goodness-of-fit of allometric growth models showed that models for resin-tapped *Pinus massoniana* had better fit than those for non-resin-tapped trees. In the developed and tested regression models, except for leaf biomass and root biomass models, the remaining models achieved acceptable performance statistics. Models for stem, bark, and aboveground biomass performed best (models 4, 4, and 7). These models have critical applications in forestry management, providing scientific evidence for biomass estimation and management of *Pinus massoniana* plantations under resin tapping disturbance.

Keywords: Resin tapping disturbance; Biomass allocation; allometric models; *Pinus masson*

iana Plantation

1. Introduction

Afforestation and reforestation are effective means to enhance carbon storage, mitigate the impacts of climate change, and improve other ecosystem services. The total planted forest area is approximately 131 million hectares, accounting for 3% of the world's forest area (FAO, 2020). Planted forests play a significant role in terrestrial ecosystems, restoring and reconstructing forest ecosystems, providing forest products, increasing forest carbon sinks, and improving the ecological environment(Messier et al., 2022). Biomass is a crucial indicator for assessing the structure and function of forest ecosystems(Andersson et al., 2000). Accurate forest biomass estimation and its changes are fundamental for calculating carbon stocks and their variations(Peichl and Arain, 2007； Prause et al., 1984). Currently, biomass research mainly focuses on two aspects: biomass allocation and biomass estimation. Biomass allocation describes the distribution characteristics of biomass in different tissues, organs, or functional units of plants, reflecting their life history strategies. It is a core issue in ecological research(Peng et al., 2023). Clarifying the characteristics of biomass allocation not only reveals the structure and function of plants but also plays a fundamental role in studying the carbon cycle of forest ecosystems in the context of climate change (Merganičová et al., 2019)； Biomass estimation involves measuring the biomass of individual trees or entire stands within a region. It is an essential basis for quantifying forest carbon stocks and productivity, as well as predicting the functions of forest ecosystems(Alvarez et al., 2012)。

During the growth and evolution of plants, they adopt different survival strategies to adapt to environmental changes. Biomass allocation is one of the most fundamental survival strategies influenced by environmental conditions. A reasonable allocation pattern can improve species' survival capacity(Obeso, 2002). The optimal and equidistant biomass allocation hypotheses present two critical assumptions in the study of plant biomass allocation. The optimal allocation theory posits that plants adjust the biomass ratio of their organs, prioritizing the allocation to those that can acquire limited resources, thereby enhancing the ability to obtain nutrients, water, and light to maximize their growth rate(Mccarthy and Enquist, 2007)； The isokinetic/allometric allocation hypothesis states that it is a method of estimating the biomass of standing trees using easily measurable factors and predictive equations. Compared to the clear-cutting method, this approach can significantly reduce labor and material input and is less destructive(Yang et al., 2009)。In the current research, species biomass allometric growth models use power functions, linear functions(Boon, 1966)、exponential functions(Laskar et al., 2020), and power-exponential functions(West et al., 1997). Biomass allometric growth models use tree measurement factors as variables to construct regression equations. The most used variables are tree species' diameter at breast height (D), height (H), and combined variables D'H, crown width (C), crown length (CL), wood density (p), and age (A). Since diameter at breast height is easy to measure, most biomass models select it as a variable, but obtaining other factors is relatively tricky(Sierra et al., 2007; Basuki et al., 2009). In the absence of diameter at breast height measurements or when young trees have not reached the measurement threshold, it is usually necessary to measure the ground diameter to estimate the timber yield and other values, such as assessing the damage caused by adverse environmental conditions like wind and fire, investigating the condition of forest land after illegal logging and estimating the logging time, calculating the volume and economic loss caused by illegal logging, and predicting the growth of trees after logging(Chukwu and Osho, 2018); (Sun Xingli et al., 2023), Considering the availability and accuracy, this paper uses diameter at breast height, tree height, and ground diameter as essential variables to construct biomass allometric growth models suitable for *Pinus massoniana* forests under resin tapping disturbance.

Pinus massoniana Lamb. It is a significant afforestation and timber species in southern China, widely distributed across 16 provinces (regions and municipalities), including Guangxi, Guangdong, Hunan, Guizhou, Fujian, and Zhejiang, accounting for more than half of the forest stock in southern China(Meng Xiangjiang et al., 2018), It proliferates, with high resin yield, making it an essential component of forestry operations south of mountainous areas and a pillar industry in forestry. Its moderate wood density makes it widely used in construction, furniture, and packaging materials(Hu La et al., 2018). Pine resin is a secondary metabolite of pine species, mainly composed of rosin, turpentine, and a small amount of water. It has many uses and is an essential raw material for forest chemical products(Jia et al., 2023). China has long been the world's largest producer of pine resin, and *Pinus massoniana* resin is a distinctive product due to its unique chemical composition. Resin tapping has a particular impact on stand growth and wood quality. Most studies indicate that the annual growth of near-mature stands has stabilized, so resin tapping has relatively little effect on their growth. However, in young and middle-aged forests, which are in vigorous growth stages with active physiological metabolism, resin tapping significantly affects their growth as it requires the consumption of substantial organic material (Chen Guangcai et al., 2016; Yang Zhangqi, 2014). Currently, research on the biomass allocation of *Pinus massoniana* plantations mainly focuses on biomass and productivity allocation characteristics at different growth stages(Ali et al., 2019a), site conditions and plantation productivity(Ding Guijie, 2000), planting density and biomass(Ali et al., 2019b), mixed planting measures and biomass(You et al., 2018), thinning measures and productivity(Deng et al., 2020), and fertilization measures and productivity(Wang et al., 2022), However, studies on the impact of resin tapping on biomass allocation and height-diameter allometric growth dynamics of *Pinus massoniana* are unclear and limited to aboveground parts. Few studies focus on the changes in biomass allocation of roots, stems, and leaves, and there is a lack of comparative studies on the allometric growth processes between aboveground and belowground parts and among different organs. This study focuses on *Pinus massoniana* plantations in the South Subtropical Region of Guangxi, exploring the impact of resin tapping on biomass allocation patterns and the allometric growth relationships between aboveground and belowground parts and among different organs. Our objectives are: (1) To investigate the effects of resin tapping disturbance on biomass characteristics and allocation patterns of different organs in *Pinus massoniana* plantations; (2) To examine the correlations between various variables and biomass components under resin tapping disturbance; and (3) To construct allometric growth models between aboveground and belowground parts and among different organs, and explore the optimal biomass models and predictive variables. We hypothesize that (1) Resin tapping disturbance significantly affects biomass characteristics and allocation patterns of different organs in *Pinus massoniana*; (2) Resin tapping disturbance influences the relationships between aboveground, belowground, and total biomass in *Pinus massoniana* plantations; and (3) Resin tapping disturbance affects the allometric growth relationships in *Pinus massoniana* plantations. This study provides a reference for adjusting regional carbon balance, mitigating climate change, and achieving high-yield, high-quality cultivation and sustainable management of *Pinus massoniana* plantations. It aims to provide a basis for estimating carbon stocks in dual-purpose forests and enriches the cultivation techniques of *Pinus massoniana* to enhance its ecological and economic value.

2. Material and methods

2.1. Description of the study area

The research was conducted in the Qingshan Experimental Forest, part of the Tropical Forestry Experimental Center of the Chinese Academy of Forestry, located in Pingxiang City, Guangxi (106°51′–106°53′ E, 22°02′–22°04′ N). This area lies along the southern subtropical zone's southern fringe (Figure 1). The climate features an annual mean temperature of 21.5°C, with January being the coldest month, averaging 13.5°C, and July the warmest at 27.6°C. The region experiences approximately 1400 mm of annual precipitation. The terrain of Daqing Mountain is varied, with the central peak rising to 1045 meters and the valleys ranging from 130 to 150 meters in elevation. Regarding soil classification, the predominant zonal soil is Ferralsols (red soil) in the Chinese soil system, Oxisols according to the soil taxonomy, or Ferralsols in the World Reference Base for Soil Resources. These soils are generally derived from medium-acid volcanic rocks and granite, with an average depth of 0.5 to 1.0 meters.

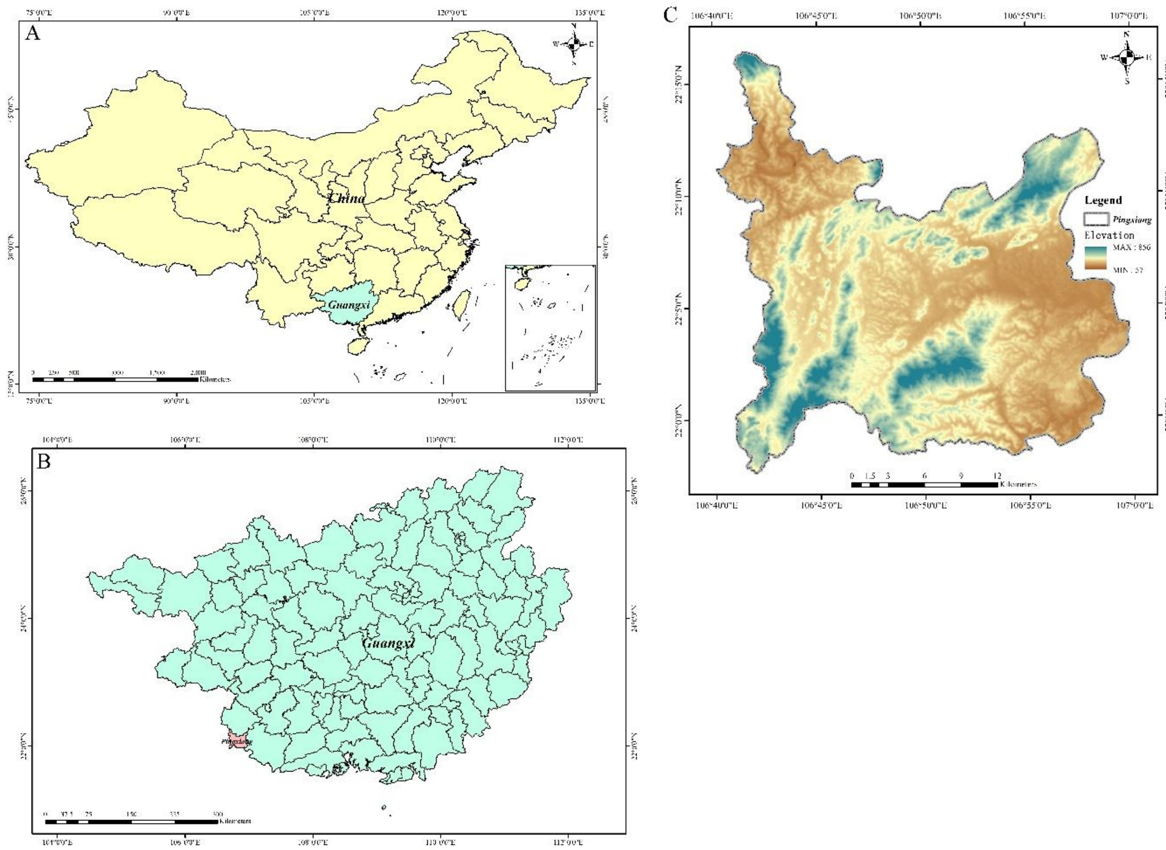


Figure 1. (A) The location of Guangxi in China. (B) Pingxiang city's geographical position within Guangxi. (C) A topographic depiction of Pingxiang city.

2.2 Research Methods

This study used the graded standard tree method, selecting ten 32-year-old *Pinus massoniana* trees of different diameter classes and complete crowns, with a 2 cm diameter class interval, for whole-tree excavation and detailed measurement. The experimental tools included a laser hypsometer, diameter, and measuring tape. The biomass of the standard trees was determined according to the "Technical Regulations for Continuous Forest Resource Inventory" (State Administration for Market Regulation, 2020). The steps were as follows: Trunk processing: Felling started from 0.3 meters above the tree base, and then a log section was cut every 1 meter towards the top of the tree at positions such as 1.3 meters, 2.3 meters, 3.3 meters, etc. If the last section was less than 1 meter, it was treated as the tree top. Each log section was weighed for its fresh weight, and a 3 to 5-cm thick disk was cut from the bottom of each section. The disks were weighed for fresh weight and taken to the laboratory for further processing as trunk samples. The tools used included a chainsaw, handsaw, 100 kg scale, and 10 kg scale. Leaf processing: All leaves were collected from the east, south, west, and north sides of the crown, placed in separate bags and weighed for fresh weight. Then, a random sample of leaves, representing 5% of the total fresh weight from each bag, was taken as leaf samples for further processing in the laboratory. Branch processing: All branches were weighed for their fresh weight, and 5% of the branches, selected randomly based on their thickness, were taken as samples for further processing in the laboratory. All samples (including leaves, branches, and trunks) were dried at 80°C to a constant weight and then weighed for their dry weight. The drying equipment used was the YLE-2000 electric thermostatic blast drying oven (Shanghai Lichen Instrument Technology Co., Ltd.).

2.3 Data Processing

The *Pinus massoniana* trees in the experimental plots were harvested, and growth indicators (ground diameter, tree height, and diameter at breast height) were measured for each plot. The branches, leaves, trunks, and bark of *Pinus massoniana* were sorted, and the roots were taken back to the laboratory for cleaning. All processed samples were then placed in an oven at 65°C, dried to a constant weight, removed, and weighed to record their dry weight. From these, leaf biomass (L), branch biomass (Br), bark biomass (Ba), stem biomass (S), and root biomass (R) were obtained. Root biomass consisted of fine root biomass (Rf-C), coarse root biomass (Rcf-C), and root head and large root biomass (Rs&l-C). Aboveground biomass (AB), total biomass (B), leaf mass ratio (R1), branch mass ratio (R2), bark mass ratio (R3), stem mass ratio (R4), root mass ratio (R5), root-to-shoot ratio (R6), root-to-leaf ratio (R7), and aboveground mass ratio (R8) were calculated.

$$R1=L/Bt \quad (1)$$

Where: R1 represents the leaf mass ratio; L represents leaf biomass (kg); Bt represents total biomass (kg).

$$R2=B2/Bt \quad (2)$$

Where: R2 represents the branch mass ratio; B2 represents branch biomass (kg).

$$R3=B3/Bt \quad (3)$$

Where: R3 represents the bark mass ratio; B3 represents bark biomass (kg).

$$R4=B4/Bt \quad (4)$$

Where: R4 represents the stem mass ratio; B4 represents stem biomass (kg).

$$R5=Br/Bt \quad (5)$$

Where: R5 represents the root mass ratio; Br represents root biomass (kg).

$$R6=Br/Ba \quad (6)$$

Where: R6 represents the root-to-shoot ratio; Ba represents aboveground biomass (kg).

$$R7=Br/L \quad (7)$$

Where: R7 represents the root-to-leaf ratio.

$$R8=Ba/Bt \quad (8)$$

Where: R8 represents the aboveground mass ratio.

Nonlinear equations were used to establish allometric biomass models for different components of resin-tapped and non-resin-tapped *Pinus massoniana*:

$$Y = aX_1^{P1}X_2^{P2}X_3^{P3}\cdots\cdots X_n^{P_n}\theta \quad (9)$$

In the equation, Y represents biomass, X is the independent variable, a and P1 to Pn are the equation parameters, and θ is the multiplicative error. To eliminate heteroscedasticity, the variance was log-transformed:

$$\ln Y = P_0 + P_1\ln X_1 + P_2\ln X_2 + P_3\ln X_3 + \cdots\cdots + P_n\ln X_n + \varepsilon \quad (10)$$

$$P_0 = \ln a_0, \boldsymbol{\varepsilon} = \ln\theta \quad (11)$$

$$Y = \exp(P_0 + P_1\ln X_1 + P_2\ln X_2 + P_3\ln X_3 + \cdots\cdots + P_n\ln X_n) + \varepsilon \quad (12)$$

Diameter at breast height (D), tree height (H), and ground diameter (C) were chosen as variables to set up univariate, bivariate, and multivariate equations, namely:

$$Y = \exp(P_0 + P_1\ln D) + \varepsilon \quad (13)$$

$$Y = \exp(P_0 + P_1\ln H) + \varepsilon \quad (14)$$

$$Y = \exp(P_0 + P_1\ln C) + \varepsilon \quad (15)$$

$$Y = \exp(P_0 + P_1\ln(D^2H)) + \varepsilon \quad (16)$$

$$Y = \exp(P_0 + P_1\ln D + P_2\ln H) + \varepsilon \quad (17)$$

$$Y = \exp(P_0 + P_1\ln D + P_2\ln C) + \varepsilon \quad (18)$$

$$Y = \exp(P_0 + P_1\ln(D^2H) + P_2\ln C) + \varepsilon \quad (19)$$

$$Y = \exp(P_0 + P_1\ln D + P_2\ln H + P_3\ln C) + \varepsilon \quad (20)$$

$$Y = \exp(P_0 + P_1\ln(D \times H \times C)) + \varepsilon \quad (21)$$

All data processing and analysis were completed in Excel 2016, SPSS 22.0, and the R Statistical Software version 4.2.1. The goodness-of-fit of the models was estimated using the adjusted coefficient of determination (R^2), root mean square error (RMSE), and mean prediction error (MPE) to identify the optimal biomass prediction model.

3 Results

3.1 Total biomass and organ-specific biomass of *Pinus massoniana* under resin tapping disturbance

The changes in biomass of different organs of *Pinus massoniana* under resin tapping disturbance are shown in Figure 2. After resin tapping disturbance, the biomass of all organs of *Pinus massoniana* decreased. The biomass of leaves, branches, bark, stems, roots, aboveground parts, and total biomass decreased by 29.07%, 44.71%, 33.44%, 34.41%, 34.48%, 35.60%, and 35.46%, respectively. No significant differences existed in the biomass of leaves and branches between resin-tapped and non-resin-tapped *Pinus massoniana* ($P>0.05$). However, there were substantial differences in the stems, bark, roots, aboveground parts, and total biomass between resin-tapped and non-resin-tapped *Pinus massoniana* ($P<0.05$).

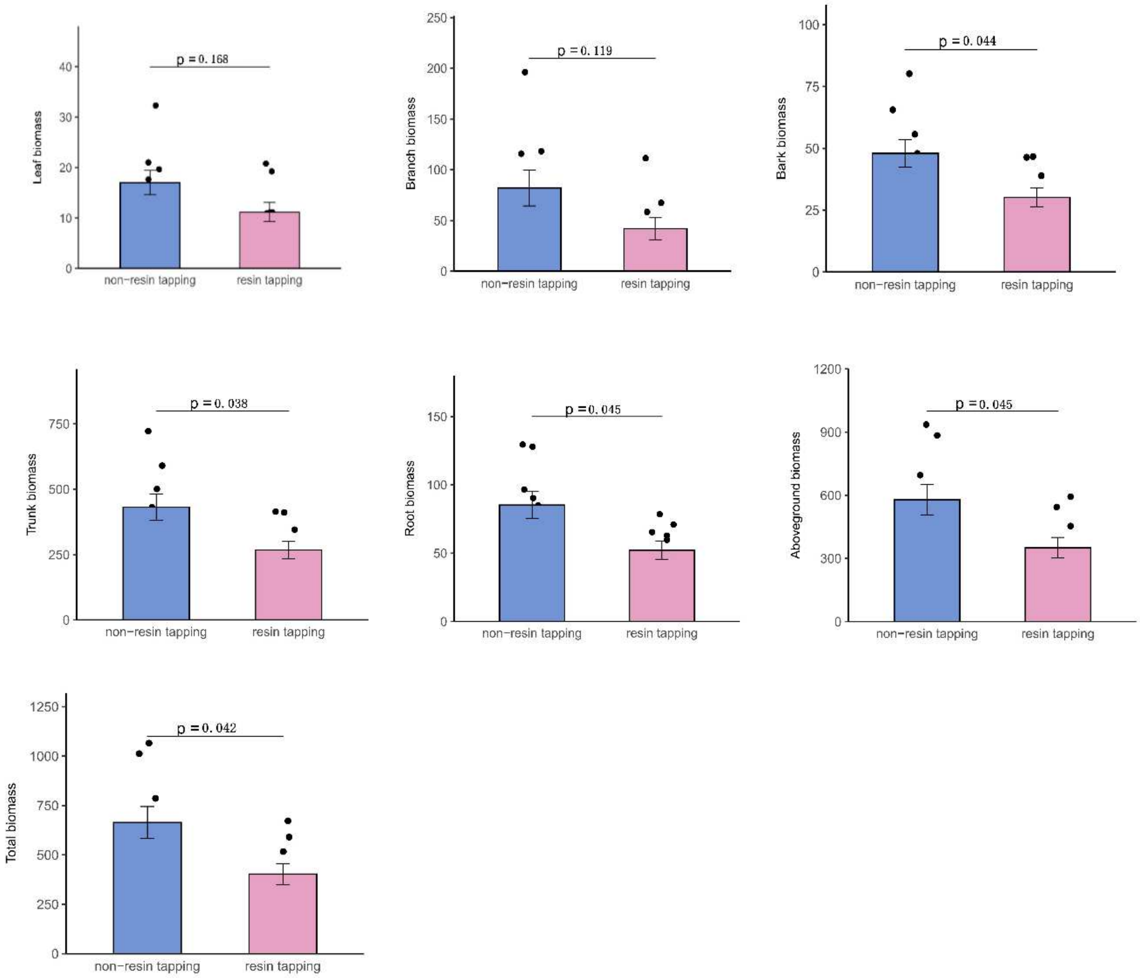


Figure 2. The impact of resin tapping on the biomass of different organs in *Pinus massoniana* plantations

3.2 Biomass Allocation Patterns of *Pinus massoniana* Organs under Resin Tapping Disturbance

The impact of resin tapping on the biomass allocation of leaves, branches, bark, stems, and roots in *Pinus massoniana* plantations is shown in Figure 3. Under resin tapping treatment, there were no significant differences in leaf mass ratio, branch mass ratio, bark mass ratio, stem mass ratio, and root mass ratio compared to non-resin tapping ($P>0.05$). Similarly, root-to-shoot ratio, root-to-leaf ratio, and aboveground mass ratio showed no significant differences compared to non-resin tapping ($P>0.05$). The biomass of both resin-tapped and non-resin-tapped trees was mainly concentrated in the stems, with stem biomass accounting for 66.51%±1.26% and 66.17%±1.48% of the aboveground total biomass, respectively. The following highest proportion was in the roots, accounting for 14.12%±1.31% and 12.79%±0.77%, respectively, while the leaves had the minor proportion, accounting for 2.68%±0.56% and 2.48%±0.61%, respectively. At the whole-tree level, biomass allocation for resin-tapped and non-resin-tapped trees showed the pattern: stem > root > branch > bark > leaf.

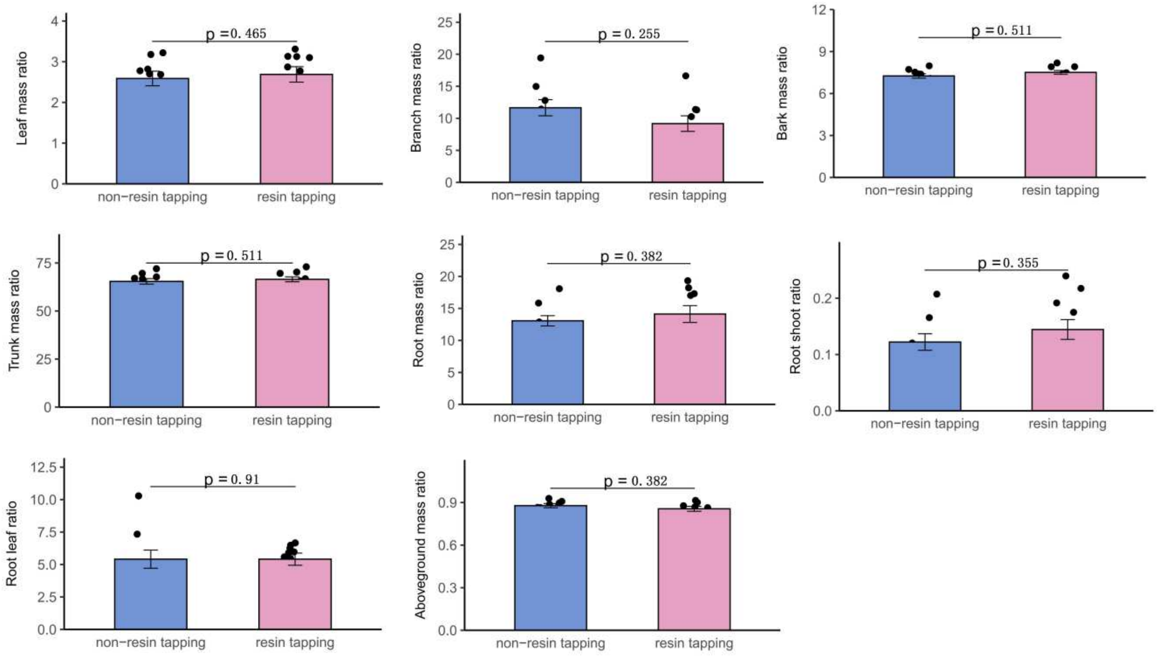


Figure 3. The Impact of Resin Tapping on Biomass Allocation in Different Organs of *Pinus massoniana* Plantations

3.3 Correlations Between Various Variables and Biomass Components of *Pinus massoniana* Under Resin Tapping Disturbance

Correlation analysis was conducted between the growth factors of resin-tapped and non-resin-tapped *Pinus massoniana* plantations and the biomass of different components (Figure 4). In non-resin-tapped *Pinus massoniana* plantations, the correlation between tree growth factors and the biomass of different components was potent. Except for the correlations of tree height (H) with leaf biomass (L), root biomass (R), ground diameter (C), and branch biomass (Br), which were not significant, other pairs of tree height, ground diameter, diameter at breast height (D), and biomass showed substantial or highly significant positive correlations. The highest correlation coefficients were found between aboveground biomass (AB) and total biomass (B) and between stem biomass (S) and bark biomass (Ba), with a correlation coefficient of 1.00. Tree height (H) was significantly correlated with aboveground biomass (AB), diameter at breast height (D), stem biomass (S), bark biomass (Ba), and total biomass (B), but the correlation coefficients were relatively low. In resin-tapped *Pinus massoniana* plantations, the correlation between tree growth factors and the biomass of different components remained strong. Still, the number of significant indicators between pairs of traits decreased compared to non-resin-tapped trees. The correlations of tree height (H) with all indicators were not substantial, and root biomass (R) showed no significant correlations with tree height (H), stem biomass (S), bark biomass (Ba), aboveground biomass (AB), branch biomass (Br), and leaf biomass (L). Other pairs of ground diameter, diameter at breast height, and biomass showed significant or highly significant positive correlations. The highest correlation coefficients were between stem biomass (S) and bark biomass (Ba) and aboveground biomass (AB), and between aboveground biomass (AB) and bark biomass (Ba) and total biomass (B), with a correlation coefficient of 1.00. Root biomass (R) showed significant correlations with D^2H, diameter at breast height (D), and total biomass (B), but the correlation coefficients were relatively low.

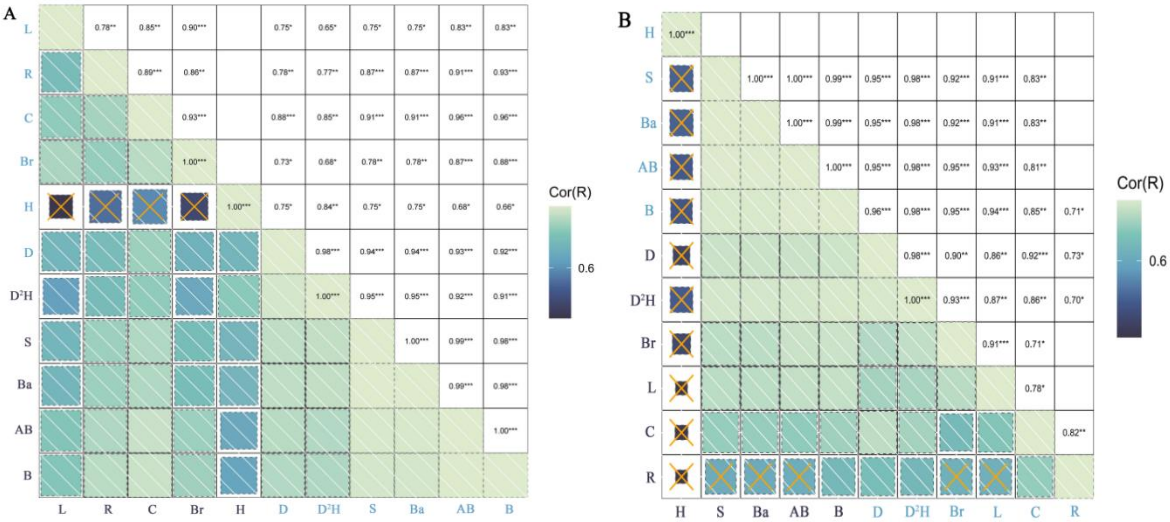
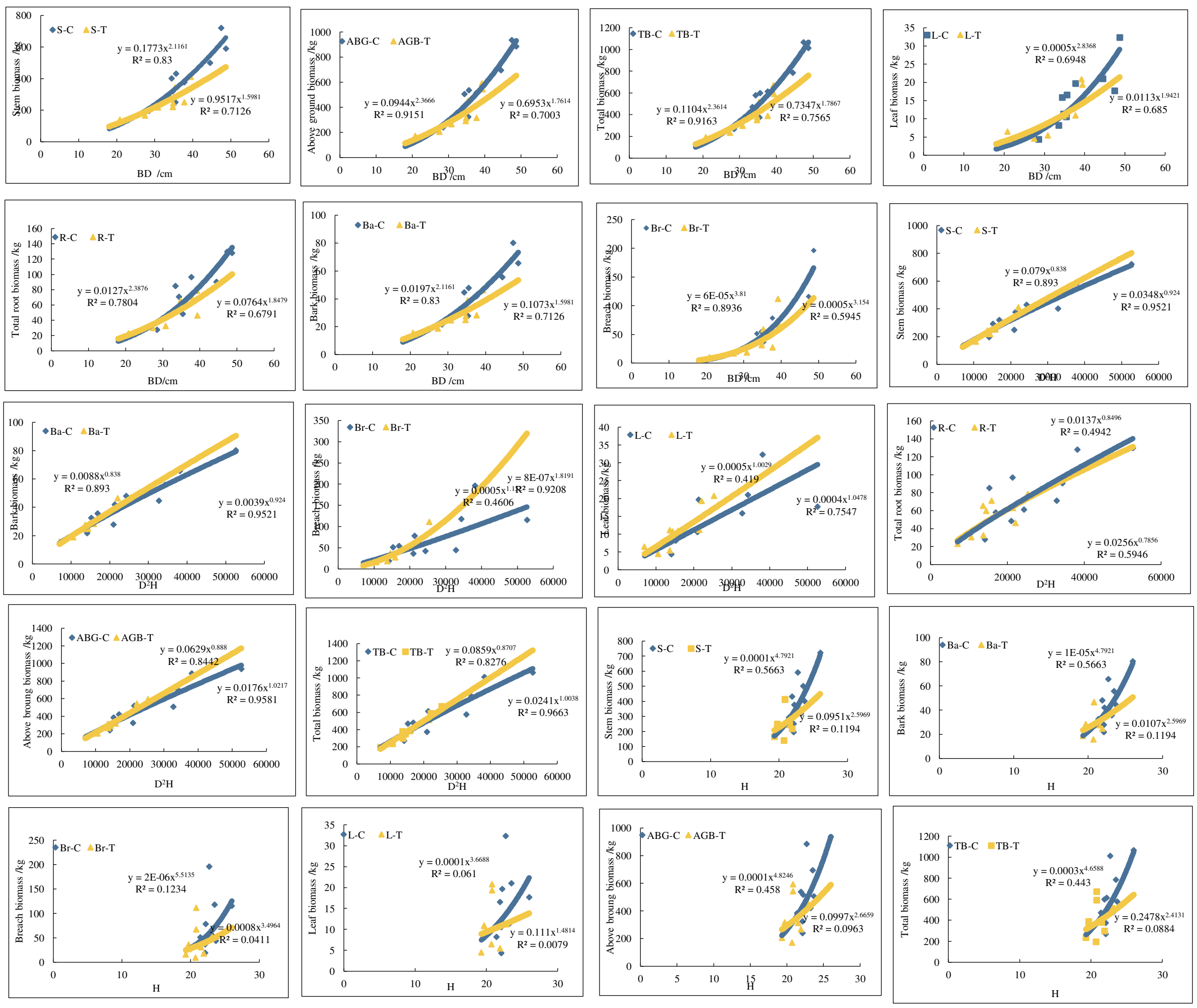


Figure 4. Correlation Between Tree Growth Factors and Biomass Components in Resin-Tapped and Non-Resin-Tapped *Pinus massoniana* Plantations. A: Non-Resin-Tapped. B: Resin-Tapped . D: heigh, H: tree height, C: ground diameter. S: Stem Biomass. Ba: Bark Biomass. Br: Branch Biomass). L: Leaf Biomass. R: Root Biomass. Q: Aboveground Biomass. Z: Total Biomass.



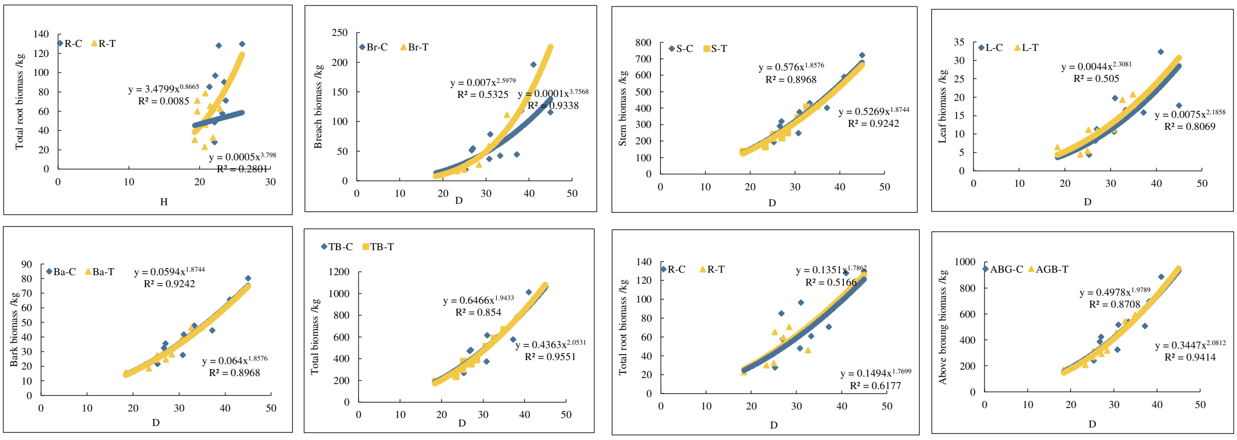


Figure 5. Curve Fitting of Diameter at Breast Height (D), Tree Height (H), and Ground Diameter (C) with Biomass Components in Resin-Tapped and Non-Resin-Tapped *Pinus massoniana* Plantations

In non-resin-tapped Pinus massoniana plantations, ground diameter (C) better fits branch biomass, leaf biomass, root biomass, aboveground biomass, and total biomass compared to other variables. D^2H provides a better fit for stem biomass, and diameter at breast height (D) provides a better fit for bark biomass. In resin-tapped Pinus massoniana plantations, ground diameter (C) better fits root biomass. D^2H provides a better fit for stem biomass, bark biomass, branch biomass, aboveground biomass, and total biomass than other variables. The breast height (D) diameter better fits leaf biomass. The optimal fitting equation variables for different parts of resin-tapped and non-resin-tapped Pinus massoniana plantations vary significantly. Tree height (H) provides a poorer fit for the biomass of various components of Pinus massoniana compared to other variables(Figure 5).

3.4 Allometric Growth Models of *Pinus massoniana* Under Resin Tapping Disturbance

Based on different variables, formulas (1) to (9) were applied to establish nine allometric biomass models for various components of resin-tapped and non-resin-tapped *Pinus massoniana* plantations. The goodness-of-fit (adjusted R^2, MPE, RMSE) varied among the models. For non-resin-tapped *Pinus massoniana*, the adjusted R^2 ranged from 0.026 to 0.921, MPE ranged from 0.739 to 16.54, and RMSE ranged from 4.294 to 186.372. For resin-tapped *Pinus massoniana*, the adjusted R^2 ranged from -0.196 to 0.957, MPE ranged from 0.279 to 26.052, and RMSE ranged from 2.446 to 146.603. The overall fit for resin-tapped *Pinus massoniana* was better than that for non-resin-tapped *Pinus massoniana*. The three models with the highest goodness-of-fit for each component of resin-tapped and non-resin-tapped *Pinus massoniana* were selected, as shown in Tables 1 and 2. For non-resin-tapped *Pinus massoniana*, stem biomass, bark biomass, branch biomass, leaf biomass, root biomass, aboveground biomass, and total biomass were best fitted by models 9, 9, 7, 8, 8, 7, and 7, respectively, with variables (DHC), (DHC), (D^2H, C), (D, H, C), (D, H, C), (D^2H, C), and (D^2H, C). For resin-tapped *Pinus massoniana*, stem biomass, bark biomass, branch biomass, leaf biomass, root biomass, aboveground biomass, and total biomass were best fitted by models 4, 4, 6, 6, 3, 7, and 4, respectively, with variables (D^2H), (D^2H), (D, C), (D, C), (C), (D^2H, C), and (D^2H). Tables 3 and 4 show the biomass models using only diameter at breast height (D) as a single variable. Comparatively, the goodness-of-fit of these models was significantly lower.

Table 1: Allometric Growth Models for Biomass Components of Non-Resin-Tapped *Pinus massoniana*

Components	Models	P0	P1	P2	P3	R2	MPE	RMSE
	M(6)	-1.598	1.053	1.064		0.86	-0.81	43.39
S (Stem Biomass)	M(7)	-2.764	0.473	1.082		0.86	-0.78	40.98
	M(9)	-3.81	0.951			0.88	-0.79	39.97
	M(6)	-2.491	1.053	1.064		0.86	-0.81	4.82
Ba (Bark Biomass)	M(7)	-3.656	0.473	1.082		0.86	-0.78	4.56
	M(9)	-4.703	0.951			0.88	-0.79	4.44
	M(6)	-9.837	-1.149	4.957		0.92	-1.33	11.82
Br (Branch Biomass)	M(7)	-8.566	-0.515	4.937		0.92	-1.30	10.36
	M(8)	-8.218	-0.985	-0.65	4.93	0.91	-1.30	10.04
	M(6)	-3.673	0.716	2.019		0.72	-3.50	4.48
L (Leaf Biomass)	M(7)	-4.626	0.331	2.033		0.73	-3.52	4.50
	M(8)	-4.179	0.708	0.235	1.994	0.73	-3.30	4.40
	M(6)	-4.388	-0.141	2.529		0.78	-6.39	14.58
R (Root Biomass)	M(7)	-4.197	-0.079	2.561		0.78	-6.38	14.58
	M(8)	-2.916	0.008	-0.596	2.494	0.79	-6.39	14.56
	M(6)	-2.263	0.776	1.592		0.88	-0.82	56.63
Q (Aboveground Biomass)	M(7)	-3.104	0.34	1.622		0.89	-0.74	49.46
	M(8)	-2.746	0.727	0.196	1.603	0.87	-0.74	49.18
	M(3)	-2.204	2.361			0.87	-0.99	72.18
Z (Total Biomass)	M(6)	-2.123	0.647	1.716		0.88	-0.82	59.74
	M(7)	-2.818	0.281	1.747		0.88	-0.82	59.67

Table 2 Allometric Growth Models for Biomass Components of Resin-Tapped *Pinus massoniana*

Components	Models	P0	P1	P2	P3	R2	MPE	RMSE
	M(4)	-3.357	0.924			0.94	-0.33	21.74
S (Stem Biomass)	M(5)	-4.853	1.799	1.471		0.92	-0.29	22.58
	M(7)	-3.690	1.070	-0.308		0.93	-0.30	21.69
	M(4)	-5.540	0.924			0.94	-0.33	2.45
Ba (Bark Biomass)	M(5)	-7.035	1.799	1.471		0.92	-0.29	2.55
	M(7)	-5.872	1.070	-0.308		0.93	-0.30	2.45
	M(4)	-14.009	1.819			0.87	-2.39	10.30
Br (Branch Biomass)	M(6)	-8.674	4.812	-1.054		0.92	-2.18	7.53
	M(8)	-11.559	4.652	1.000	-0.946	0.89	-2.07	7.91
	M(4)	-7.778	1.048			0.68	-4.76	2.82
L (Leaf Biomass)	M(5)	-5.229	2.180	0.116		0.69	-4.60	2.60
	M(6)	-4.944	1.940	0.245		0.69	-4.56	2.60

	M(3)	-2.572	1.848		0.63	-2.13	10.67
R (Root Biomass)	M(6)	-2.451	-0.508	2.292	0.58	-2.06	10.53
	M(7)	-1.941	-0.186	2.178	0.57	-2.08	10.56
	M(4)	-4.041	1.022		0.94	-0.41	31.18
Q (Aboveground Biomass)	M(5)	-5.098	2.008	1.408	0.93	-0.40	32.73
	M(7)	-4.448	1.201	-0.377	0.94	-0.38	30.29
	M(4)	-3.725	1.004		0.96	-0.35	29.34
Z (Total Biomass)	M(5)	-4.166	1.993	1.165	0.95	-0.35	30.25
	M(7)	-3.731	1.006	-0.005	0.95	-0.35	29.34

Table 3: Allometric Growth Models for Biomass Components of Non-Resin-Tapped *Pinus massoniana* Using Diameter at Breast Height as a Variable

Components	Models	P0	P1	R2	MPE	RMSE
S (Stem Biomass)	M(1)	-0.552	1.858	0.82	-1.19	49.39
Ba (Bark Biomass)	M(1)	-2.749	1.858	0.82	-1.19	5.49
Br (Branch Biomass)	M(1)	-4.962	2.598	0.50	-9.45	35.53
L (Leaf Biomass)	M(1)	-5.437	2.308	0.60	-5.29	5.42
R (Root Biomass)	M(1)	-1.901	1.77	0.62	-8.71	19.43
Q (Aboveground Biomass)	M(1)	-0.698	1.979	0.76	-1.78	78.70
Z (Total Biomass)	M(1)	-0.436	1.943	0.76	-1.78	94.77

Table 4: Allometric Growth Models for Biomass Components of Resin-Tapped *Pinus massoniana* Using Diameter at Breast Height as a Variable

Components	Models	P0	P1	R2	MPE	RMSE
S (Stem Biomass)	M(1)	-0.641	1.874	0.91	-0.58	27.13
Ba (Bark Biomass)	M(1)	-2.823	1.874	0.91	-0.58	3.06
Br (Branch Biomass)	M(1)	-8.880	3.757	0.88	-2.51	9.88
L (Leaf Biomass)	M(1)	-4.896	2.186	0.73	-4.60	2.58
R (Root Biomass)	M(1)	-2.001	1.786	0.43	-3.19	13.20
Q (Aboveground Biomass)	M(1)	-1.065	2.081	0.92	-0.67	36.62
Z (Total Biomass)	M(1)	-0.829	2.053	0.94	-0.53	33.97

4. Discussion

4.1The Impact of Resin Tapping on the Total Biomass and Organ-Specific Biomass of *Pinus massoniana* Plantations

Forest biomass and productivity are influenced by various factors, including climate, soil, water-heat conditions, and forest type(Xu et al., 2024； Li et al., 2019； Chen et al., 2023); for plantations, tree species, stand age, afforestation patterns, and management activities all affect stand biomass and productivity (Zeng et al., 2021； Kumi et al., 2021； Cukor et al., 2022). Reports suggest that resin tapping positively affects the radial growth of Scots pine trees at breast height but does not affect growth above the tapping face (Mag nuszewski, 2009). However, studies in Greece, Spain, and China indicate that pine growth is negatively impacted by resin extraction, likely due to carbohydrates being diverted from tree growth to excessive resin production(Xu Huilan et al., 2022；Papadopoulos, 2013; Génova et al., 2014; Chen et al., 2015)likely as a result of carbohydrates not being invested in tree growth but in excess resin production. This study found that under resin tapping disturbance, the biomass of all organs of *Pinus massoniana* decreased. The biomass of leaves, branches, bark, stems, roots, aboveground parts, and total biomass decreased by 29.07%, 44.71%, 33.44%, 34.41%, 34.48%, 35.60%, and 35.46%, respectively. The biomass of leaves and branches in resin-tapped *Pinus massoniana* did not show significant differences compared to non-resin-tapped *Pinus massoniana* ($P>0.05$). However, the biomass of stems, bark, roots, aboveground parts, and total biomass in resin-tapped *Pinus massoniana* showed significant differences compared to non-resin-tapped *Pinus massoniana* ($P<0.05$). The main components of pine resin are organic compounds synthesized by trees, such as resin acids, which are rich in phosphorus(Sarria-Villa et al., 2021); tapping may lead to phosphorus loss within the trees, causing them to absorb more phosphorus from the soil to sustain their growth, thereby reducing the total phosphorus content in the soil and affecting the nutrient supply to the trees (Cai Tianpei and Liu Xijun; Cheng Kehua, 2024). The resin tapping process involves cutting into the xylem to access the resin ducts, which reduces sap flow from the roots to the crown and blocks the transport of photosynthetic products (such as soluble sugars and starch) from sources to sinks. As resin tapping continues, soluble sugars and starch concentration in the bark significantly decreases(Yan Lifen and Zhao Fengxia, 2021). Resin tapping destroys the xylem and bast fibers of the trunk portion of P. massoniana, affecting tree growth and the ectomycorrhizal (EMF) community by impeding water and nutrient transport and increasing the effective potassium content of the soil (Magnuszewski, 2009). These changes indicate that resin tapping affects the physiological functions and overall ecosystem health of *Pinus massoniana*, thereby impacting the biomass of its various organs.

4.2 The Impact of Resin Tapping on Biomass Allocation in Different Organs of *Pinus massoniana* Plantations

Reasonable biomass allocation is crucial for the survival and reproduction of species(Tang et al., 2022). The balanced growth hypothesis suggests that plants prioritize resource allocation to the most needed organs to obtain scarce resources in the environment more effectively. When one organ gains resources, others must pay the corresponding price (McConnaughay and Coleman, 1999). Plant species have different biomass allocation strategies to better adapt to their environment(Lambers and Oliveira, 2019). Biomass allocation in plants refers to the distribution of limited resources to different organs or structural functions, which reflects the plant's potential growth characteristics and helps it better adapt to environmental changes(Hu et al., 2021； Zheng et al., 2024). A reasonable biomass allocation pattern helps enhance plant survival capacity. The allocation pattern of biomass among different organs is influenced by external environmental factors(Biehl et al., 2023； Rosenvald et al., 2014)、species differences(Mankou et al., 2021； Zhang et al., 2023)、plant age(Deng et al., 2024)、and fertilization(He et al., 2020). This study found that under resin-tapping treatment, there were no significant differences in leaf mass ratio, branch mass ratio, bark mass ratio, stem mass ratio, and root mass ratio compared to non-resin-tapped trees (P>

0.05). Similarly, the root-to-shoot ratio, root-to-leaf ratio, and aboveground mass ratio showed no significant differences compared to non-resin-tapped trees (P>0.05). The biomass of all organs in *Pinus massoniana* decreased under resin tapping treatment. The biomass of leaves, branches, bark, stems, roots, aboveground parts, and total biomass decreased by 29.07%, 44.71%, 33.44%, 34.41%, 34.48%, 35.60%, and 35.46%, respectively, with little difference in the reduction among organs. Pine resin is stored in the resin duct system of pine needles, branches, and stems' xylem and phloem(López-Álvarez et al., 2023). Resin tapping affects the overall physiological and metabolic processes of trees(Garcia-Forner et al., 2021) ， increases tree mortality rates(Zevgolis et al., 2022) , and reduces the non-structural carbohydrate content in the phloem and roots(Du et al., 2022). After resin tapping, the biomass allocation ratios of different organs in *Pinus massoniana* plantations gradually became consistent with the non-resin-tapped state. This indicates that *Pinus massoniana* can adapt to resin tapping disturbance through reasonable biomass allocation, demonstrating its ability to balance resource distribution. This ability helps *Pinus massoniana* maintain average growth in long-term resin-tapping environments and may be one of the mechanisms behind its strong ecological adaptability to resin-tapping conditions. It is generally believed that stem biomass is the largest among the biomass of different organs, accounting for about half of the aboveground total biomass(Zhou et al., 2021). In this study, the biomass of both resin-tapped and non-resin-tapped trees was mainly concentrated in the stems, with stem biomass accounting for 66.51%±1.26% and 66.17%±1.48% of the aboveground total biomass, respectively. The highest proportion was in the roots, accounting for 14.12%±1.31% and 12.79%±0.77%, respectively. The leaves had the most minor proportion, accounting for 2.68%±0.56% and 2.48%±0.61%, respectively. At the whole-tree level, biomass allocation for resin-tapped and non-resin-tapped trees followed the pattern: stem ＞ root ＞ branch ＞ bark ＞ leaf.

4.3The Impact of Resin Tapping on Allometric Growth Relationships in *Pinus massoniana*

Diameter at breast height (D) is the most used and easily measured indicator in biomass models. Biomass models using D as a single variable often achieve high accuracy (Xie et al., 2022; Xu et al., 2022). This study found a strong correlation between D and the growth and biomass of different components in resin-tapped and non-resin-tapped *Pinus massoniana* plantations. In non-resin-tapped plantations, D provided a better fit for bark biomass than other variables, while in resin-tapped plantations, D provided a better fit for leaf biomass. Models using D as the sole independent variable had high R^2 and low RMSE, indicating a robust intrinsic relationship between D and biomass, making it a key parameter in biomass models. Other studies have shown that the regression model for D. clearness using the single compound predictive variables DH (model 1) was the most robust (Nogueira et al., 2021). Tree height (H) is usually added as a second parameter in biomass models to improve estimation accuracy, but previous studies have shown varying effects of H on model accuracy. Some studies indicate that H can improve model accuracy(Wang et al., 2021; Peng et al., 2017)， while others suggest that H may reduce or have no effect on model accuracy(Gou et al., 2017). Studies have shown that including H in biomass models can offset regional impacts, and even limited sampling of heights can be used to refine height–diameter allometries (Sullivan et al., 2018). However, the study by Dutcă et al. (2018) indicates that H can only reduce the regional effect in stem biomass models but increases the regional impact on aboveground and total biomass models. (Dutcă et al., 2018) The study by Tang Shengsen found that resin tapping had no significant effect on the height growth of young loblolly *pine plantations*(Tang Shengsen and Deng Yinwei; Yang Zhangqi, 2016). This study found that in non-resin-tapped *Pinus massoniana* plantations, H was not significantly correlated with L (leaf biomass), R (root biomass), C (ground diameter), or Br (branch biomass). In resin-tapped plantations, H was not significantly correlated with any indicators. Both resin-tapped, and non-resin-tapped *Pinus massoniana* plantations showed a strong correlation between D^2H and the growth and biomass of different components. In non-resin-tapped plantations, D^2H provided a better fit for stem biomass than other variables. In resin-tapped plantations, D^2H provided a better fit for stem biomass, bark biomass, branch biomass, aboveground biomass, and total biomass than other variables. This study included H in the form of D^2H in the models, which improved the estimation accuracy of the biomass of different organs and the total biomass of *Pinus massoniana* plantations, though the improvement was limited. This is mainly because the intrinsic relationship between H and biomass is not strong enough. Trees often proliferate in height to reach the canopy in the early stages of growth and then expand laterally, resulting in trees of different diameter classes in uneven-aged forests having similar heights(Fransson et al., 2021). In actual production, when trees are felled, and diameter at breast height cannot be measured, establishing a regression relationship model between ground diameter and diameter at breast height is an effective method to estimate the volume of felled trees(Zeng Chunyang et al., 2023). Li Hui used 11 standard univariate mathematical models to fit the relationship between ground diameter and diameter at breast height in *Pinus massoniana*, finding that the power function model was optimal (Li Hui, 2020). This study found a strong correlation between ground diameter and the growth and biomass of different components in resin-tapped and non-resin-tapped *Pinus massoniana* plantations. In non-resin-tapped plantations, ground diameter provided a better fit for branch biomass, leaf biomass, root biomass, aboveground biomass, and total biomass than other variables. In resin-tapped plantations, ground diameter provided a better fit for root biomass. Models using the ground diameter as the sole independent variable had high R^2 and low RMSE, indicating a robust intrinsic relationship between ground diameter and biomass, making it a key parameter in biomass models.

Biomass allometric growth models are highly species- and region-specific(Dutcă et al., 2018); constructing biomass models for specific species and management practices in particular regions is essential for forest ecological evaluation and regional carbon sink measurement (Forsius et al., 2021). In this study, the overall fit for resin-tapped *Pinus massoniana* was better than that for non-resin-tapped *Pinus massoniana*. We believe that resin tapping may improve growth conditions by adjusting energy allocation in trees, thereby increasing the prediction accuracy of biomass models. Specifically, resin tapping may result in more regular biomass allocation in trees because this treatment affects physiological activities, forcing trees to reallocate resources to optimize essential parts for survival and regeneration, such as stems and roots. Additionally, resin tapping stimulates trees to produce more resin through wounding, which may alter biochemical processes and affect their adaptability to environmental conditions, such as sensitivity to drought or other climate conditions(Dietrich et al., 2024). This ability to adapt to resin tapping through biochemical regulation may reduce the biological variability of biomass to some extent, resulting in lower data dispersion in statistical models for resin-tapped *Pinus massoniana*, thereby improving the goodness of fit of the models. These studies indicate that resin tapping treatment directly enhances the fit of biomass models for *Pinus massoniana*, providing crucial scientific evidence for forest management and biomass estimation.

For non-resin-tapped *Pinus massoniana*, stem biomass, bark biomass, branch biomass, leaf biomass, root biomass, aboveground biomass, and total biomass were best fitted by models 9, 9, 7, 8, 8, 7, and 7, respectively, with variables (DHC), (DHC), (D^2H, C), (D, H, C), (D, H, C), (D^2H, C), and (D^2H, C). For resin-tapped *Pinus massoniana*, stem biomass, bark biomass, branch biomass, leaf biomass, root biomass, aboveground biomass, and total biomass were best fitted by models 4, 4, 6, 6, 3, 7, and 4, respectively, with variables (D^2H), (D^2H), (D, C), (D, C), (C), (D^2H, C), and (D^2H). When tree height and ground diameter were introduced as the second and third variables, the explanatory power of the biomass models generally improved, with a better fit. The R^2 of the leaf biomass allometric growth model and root biomass allometric growth model established in this study were relatively low. This is because leaf measurement is difficult during field sampling. Leaves are susceptible to light, water, nutrient, and soil conditions(Bond-Lamberty et al., 2014); their biomass is influenced by canopy density and branch position, leading to significant errors. Roots are one of the main nutrient organs in plants, playing roles in absorption, transport, and storage. They provide water and nutrients for plant growth and development and store nutrients and energy for a certain period and to a certain extent(Pernot et al., 2019). Fine root turnover is rapid, requiring a large amount of carbohydrates, and each year, a significant amount of nutrients and organic matter is returned to the surface soil through dead fine roots (Xing et al., 2024). The function of roots is closely related to their quantity, distribution, lifespan, morphology, and configuration, which are influenced by plant characteristics and external environmental factors. Additionally, roots are sensitive to soil quality and ecological changes (Dannowski and Block, 2005). This study investigated the allocation patterns of different organs in resin-tapped and non-resin-tapped *Pinus massoniana* plantations through whole-tree harvesting. It established allometric biomass models for each organ based on diameter at breast height, tree height, and ground diameter factors. The aim was to provide a theoretical basis for biomass estimation, allometric growth model optimization, and practical research methods for estimating biomass and carbon stocks in dual-purpose *Pinus massoniana* forests.

5 Conclusion

In this study, we explored the impact of resin tapping disturbance on the biomass of different components in *Pinus massoniana* plantations. The results showed that resin tapping disturbance generally led to a decrease in the biomass of various organs in *Pinus massoniana*, with the reduction in stem, bark, root, aboveground, and total biomass being statistically significant ($P<0.05$), indicating that resin tapping significantly affects biomass accumulation in these components. However, the changes in leaf and branch biomass were insignificant ($P>0.05$), suggesting that the impact of resin tapping disturbance is selective among different tree organs. Biomass allocation analysis showed that regardless of whether resin tapping was performed, biomass was mainly concentrated in the stems, accounting for about 66% of the aboveground total biomass. This result highlights the characteristic of biomass allocation in *Pinus massoniana*, which prioritizes supporting the growth of primary structures. Although there was no significant difference in biomass proportion between resin-tapped and non-resin-tapped *Pinus massoniana*, resin-tapping did not alter the overall biomass allocation pattern. Correlation analysis between growth factors and biomass in resin-tapped and non-resin-tapped *Pinus massoniana* revealed that resin-tapping affected the significance of these correlations. Notably, the correlation between tree height and other biomass components was no longer significant in resin-tapped trees, suggesting that resin-tapping may alter the growth strategy and energy allocation of *Pinus massoniana*. Comparing the goodness-of-fit of allometric growth models under different treatments showed that the models for resin-tapped *Pinus massoniana* generally had a better fit than those for non-resin-tapped *Pinus massoniana*. Specifically, the models for stem, bark, and aboveground biomass in resin-tapped *Pinus massoniana* (models 4, 4, and 7) showed the best fit, with excellent goodness-of-fit indicators (adjusted R^2, MPE, RMSE). These models are statistically valid and have significant forestry management value, providing scientific evidence for biomass estimation and management of *Pinus massoniana* plantations under resin tapping disturbance. In summary, resin tapping disturbance significantly affects the biomass allocation and growth dynamics of *Pinus massoniana* plantations. The models for stem, bark, and aboveground biomass in resin-tapped trees, with their high goodness-of-fit, are highlights of this study, providing quantitative tools for future management of *Pinus massoniana* forests to optimize resource utilization and conservation strategies. Future research can further explore changes in ecosystem services under resin tapping disturbance to provide more scientific evidence for the sustainable management of *Pinus massoniana* plantations.

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